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Departament de Producció Vegetal i Ciència Forestal

Estrategias para optimizar el uso del nitrógeno en cultivos extensivos de regadío del Valle del Ebro

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Montserrat Salmerón Cortasa

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Directores:
Dr. José Cavero Campo
Dr. Ramón Isla Climente

Tutor:
Dr. Jaume Lloveras Vilamanyà

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La producción de maíz (*Zea mays* L.) en monocultivo o en rotación con la alfalfa (*Medicago sativa* L.) es una práctica habitual en la agricultura de regadío del Valle del Ebro, siendo ambos los cultivos extensivos de regadío más importantes de esta zona debido a su alta productividad y rentabilidad. La agricultura de regadío ha sido identificada como la principal causante de contaminación difusa por nitrato de las aguas superficiales y subterráneas. La aplicación de dosis altas de purín de cerdo y la alta fertilización nitrogenada del maíz se han asociado con este problema medioambiental. En la presente tesis se han evaluado distintas estrategias agronómicas con el fin de optimizar el uso del N en cultivos extensivos de regadío del Valle del Ebro

Los resultados indican la viabilidad de aplicaciones de purín porcino a dosis baja (140 kg N ha^{-1} $año^{-1}$) y alta (340 kg N ha^{-1} $año^{-1}$) durante el periodo de crecimiento de la alfalfa (tras el primer y tercer corte), sin comprometer la producción ni calidad del forraje de alfalfa. La concentración y masa de NO_3-N y P en el agua de drenaje fue muy baja (<2 kg N ha^{-1} $año^{-1}$) y no se vio afectada por la aplicación de purín porcino. Esta práctica puede permitir la disminución de la carga de purín aplicado a otros cultivos, mejorando la eficiencia global de la gestión de este residuo ganadero.

En un experimento realizado en 12 lisímetros de drenaje se estudió como distintos cultivos cubierta (cebada (*Hordeum vulgare* L.), nabina (*Brassica rapa* L.) y veza (*Vicia sativa* L.) intercalados en un monocultivo de maíz afectan al N perdido por lavado y al rendimiento del maíz. El maíz fue fertilizado con 300 kg N ha^{-1} en el control sin cultivo cubierta y esta cantidad se redujo en los tratamientos con cultivo cubierta de acuerdo con el N acumulado por la parte aérea de los mismos. El tratamiento de veza no redujo el lavado de N ni afectó al rendimiento del maíz. El uso de los cultivos cubierta de cebada y nabina redujo el lavado en un 80 % respecto al control (25 kg N ha^{-1} $año^{-1}$). Sin embargo, pueden tener un efecto negativo en el rendimiento de maíz (2,7 t ha^{-1} menos) al disminuir la disponibilidad de N, lo que hace necesario ajustar la dosis de fertilizante nitrogenado aplicado en un maíz después de cultivos cubierta para evitar reducciones significativas en el rendimiento del cultivo.

En un experimento de campo se ensayaron dos métodos de implantación de cultivos cubierta tras maíz (siembra directa y siembra tras laboreo convencional) y cinco tipos de cultivo cubierta (cebada, nabina, colza (*Brassica napus* L.), veza, suelo desnudo (control)). El maíz fue fertilizado con 300 kg N ha^{-1} en el control y con 250 kg N ha^{-1} en el resto de tratamientos. La siembra directa permitió una fecha de siembra más temprana que el laboreo convencional lo que produjo mayor biomasa y acumulación de N de la cebada los dos años y del resto de los cultivos cubierta solo en el primer año. Los cultivos cubierta redujeron el riesgo de lavado de N al reducir el contenido en N inorgánico del suelo en primavera y en la cosecha del maíz. El primer año el rendimiento del maíz disminuyó en 4 t ha^{-1} tras cebada y el segundo año disminuyó en 1 t ha^{-1} tras cebada y nabina. Estas reducciones se debieron a una deficiencia de N como en el ensayo de los lisímetros. Las medidas de SPAD permitieron detectar la deficiencia de N y podrían usarse para corregirla cuando se usen cultivos cubierta en monocultivo de maíz.

El uso de los modelos de simulación como el DSSAT puede ayudar a extrapolar los resultados obtenidos sobre el uso de cultivos cubierta en monocultivo de maíz a otras condiciones de suelo y clima en el valle del Ebro, con el fin de conocer los beneficios potenciales de esta práctica y diseñar estrategias de manejo. Si bien el modelo no predijo adecuadamente las ligeras reducciones del rendimiento del maíz causadas por algunos cultivos cubierta, la simulación adecuada de las extracciones de N de maíz y de la disminución del lavado con el uso de los cultivos cubierta respecto a un tratamiento control permiten su uso para estudiar los efectos de esta práctica en el lavado de nitrato. En las condiciones de una cuenca regada del valle del Ebro (La Violada), el uso de la cebada como cultivo cubierta puede reducir el lavado en un 50 %. La reducción del N lavado se puede ver afectada por el tipo de suelo y la fracción de lavado usada en el cálculo del riego aplicado.

La producció de blat de moro (*Zea mays* L.) en monocultiu o en rotació amb alfals (*Medicago sativa* L.) és una pràctica comú a l'agricultura de regadiu de la Vall de l'Ebre, sent els dos cultius de regadiu més importants degut a la seva alta productivitat i rendibilitat. L'agricultura de regadiu s'ha identificat com la principal causant de la contaminació per nitrats d'aigües superficials i subterrànies. L'aplicació de dosis altes de purí porcí i l'alta fertilització nitrogenada del blat de moro s'ha associat a aquest problema mediambiental. A la present tesi s'han avaluat diferents estratègies agronòmiques amb la fi d'optimitzar l'ús del N en cultius extensius de regadiu de la Vall de l'Ebre.

Els resultats obtinguts en 12 lisímetres de drenatge indiquen la viabilitat de les aplicacions de purí porcí a dosis baixes (140 kg N ha^{-1}) i altes (340 kg N ha^{-1}) durant el període de creixement de l'alfals (rere el primer i tercer tall), sense comprometre la producció ni qualitat del farratge d'alfals. La concentració i massa de NO3-N i P a l'aigua de drenatge va ser molt baixa (< 2 kg N ha^{-1}) i no es va veure afectada per les aplicacions de purí porcí. Aquesta pràctica pot permetre la disminució de la càrrega de purí aplicat a altres cultius, millorant l'eficiència global de la gestió d'aquest residu ramader.

En un experiment realitzat en 12 lisímetres de drenatge es va estudiar cóm diferents cultius coberta (civada (Hordeum vulgare L.), nabina (Brassica rapa L.) i vesa (Vicia sativa L.)) intercalats en un monocultiu de blat de moro afecten a les pèrdues de N per rentat i al rendiment del blat de moro. El blat de moro va ser fertilitzat amb 300 kg N ha^{-1} al control i aquesta quantitat es va reduir als tractaments amb cultius coberta d'acord amb el N acumulat a la part aèria dels mateixos. El tractament de vesa no va reduir el rentat de N ni va afectar al rendiment del blat de moro. La utilització dels cultius coberta de civada i nabina va reduir el rentat en un 80 % respecte al control (25 kg N ha^{-1} any^{-1}). No obstant, poden tenir un efecte negatiu al rendiment del blat de moro (2,7 t ha^{-1} menys) al reduir la disponibilitat de N, el que fa necessari ajustar les dosis de fertilitzant nitrogenat al blat de moro després dels cultius coberta per tal d'evitar reduccions significatives del rendiment del cultiu.

En un experiment de camp es van assajar dos mètodes d'implantació de cultius coberta rere blat de moro (sembra directa i sembra rere laboreig convencional) i cinc tipus de cultiu coberta (civada, nabina, colza (*Brassica rapa* L.), vesa, sòl nu (control)). El blat de moro va ser fertilitzat amb 300 kg N ha^{-1} al control i amb 250 kg N ha^{-1} a la resta de tractaments. La sembra directa va permetre una data de sembra més primerenca que el laboreig convencional, el que va permetre una major acumulació de biomassa i de N a la civada els dos anys i a la resta de cultius coberta el primer any. Els cultius coberta van reduir el risc de rentat de N al reduir el contingut de N inorgànic al sòl a la primavera i en el moment de collita del blat de moro. El primer any el rendiment del blat de moro va disminuir en 4 t ha^{-1} rere la civada, i el segon any en 1 t ha^{-1} rere la civada i nabina. Aquestes reduccions van ser degudes a una deficiència de N com a l'assaig dels lisímetres. Les mesures de SPAD van permetre detectar deficiències de N i podrien ser utilitzades per corregir-les quan s'utilitzin cultius coberta amb blat de moro.

L'ús dels models del simulació com el DSSAT pot ajudar a extrapolar els resultats obtinguts sobre l'ús dels cultius coberta al monocultiu del blat de moro a altres condicions de sòl i clima de la Vall del Ebre, per poder conèixer els beneficis potencials d'aquesta pràctica i dissenyar estratègies de maneig. Encara que el model no va predir adequadament la reducció del rendiment del blat de moro amb determinats cultius coberta, la correcta simulació de les extraccions de N del blat de moro i de la disminució del rentat de N amb l'ús del cultius coberta respecte a un tractament control permeten el seu ús per estudiar els efectes d'aquesta pràctica al rentat de nitrat. En les condicions d'una conca regada de la Vall de l'Ebre (La Violada), l'ús de la civada com a cultiu coberta pot reduir el rentat en un 50 %. La reducció del N rentat es pot veure afectada pel tipus de sòl i la fracció de rentat utilitzada en els càlculs de reg.

ABSTRACT

Maize (*Zea mays* L.) grown in monoculture or in rotation with alfalfa (*Medicago sativa* L.) is a common practice in the irrigated areas of the Ebro River Valley, these being the two field crops more important in this area due to their high productivity and profitability. Irrigated agriculture has been identified as the main cause of diffuse nitrate contamination of surface and ground waters. Application of high rates of pig slurry and high rates of N fertilizer to maize have been linked with this environmental problem. In the present dissertation different agronomic strategies have been evaluated with the aim of optimizing N use in these two field irrigated crops of the Ebro River Valley.

The results indicate the viability of pig slurry applications at low (140 kg N ha^{-1} yr^{-1}) and high rates (340 kg N ha^{-1} yr^{-1}) during the growth period of alfalfa (after the first and third cut) without affecting alfalfa yield and quality. The NO_3-N and P concentration and loads in drainage water were very low (< 2 kg N ha^{-1} yr^{-1}) and not affected by the pig slurry applications. This practice can allow a reduction in the pig slurry loads to other field crops, improving the global efficiency of the management of this residue.

An experiment was carried out in 12 drainage lysimeters with different cover crops (barley (*Hordeum vulgare* L.), winter rape (*Brassica rape* L.) and vetch (*Vicia sativa* L.)) grown during the winter intercrop period of monoculture maize. The effect on N leaching and maize yield was studied. Maize was fertilized with 300 kg N ha^{-1} in the control and this amount was reduced in maize after a cover crop according to the N content in the cover crop biomass. The vetch treatment did not reduce N leaching or affect maize yield with respect to the control. The use of the barley and winter rape cover crops reduced N leaching by 80 % when compared to the control (25 kg N ha^{-1} yr^{-1}). However, these treatments had a negative effect on maize yields (reduction of 2.7 Mg ha^{-1}) due to a reduction of N availability, what makes necessary to adjust N fertilizer rates in a maize crop after cover crops in order to avoid significant yield reductions in maize.

In a field experiment two sowing methods for the cover crops were studied (direct sowing and sowing after conventional tillage operations), and five cover crop treatments were evaluated: barley, winter rape, oilseed rape (*Brassica napus* L.), vetch and bare soil (control). Maize was fertilized with 300 kg N ha^{-1} in the control and with 250 kg N ha^{-1} in the other treatments. Direct sowing allowed earlier planting dates than conventional sowing, what led to higher biomass and N content of the cover crops in the first year, and in barley the two years. Cover crops reduced N leaching risks by reducing soil inorganic N in spring and at maize harvest. In the first year, maize yield was reduced by 4 Mg ha^{-1} after barley and by 1 Mg ha^{-1} after barley and winter rape the second year. These yield reductions were due to a N deficiency similar to that found in the lysimeter experiment. SPAD measurements allowed to detect N deficiencies in maize and could be used to correct it when using cover crops in monoculture maize.

The use of the simulation models like DSSAT can help extrapolate the results obtained about the use of cover crops in monoculture maize to other soil and climate conditions in the Ebro River Valley, with the aim of study the benefits of this practice and to design management strategies. Although the model did not simulate accurately the observed slight reductions of maize due to the growth of some cover crops, the adequate simulation of the N taken up by maize and of the reduction in N leaching when using cover crops compared to a control treatment allows the use of the model to simulate cover crops effects on N leaching. In the conditions of and irrigated watershed of the Ebro River, the use of barley as cover crop can reduce the N leaching by 50%. This reduction of N leaching can be affected by the soil type and by the leaching fraction used to calculate the irrigation depth to apply in maize.

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Introducción general

Capítulo 1: Introducción general

1. Introducción

La producción de maíz en monocultivo o en rotación con la alfalfa es una práctica habitual en la agricultura de regadío del Valle del Ebro, siendo estos los cultivos extensivos de regadío más importantes económicamente en esta zona. La superficie dedicada a los mismos en el año 2008 fue de 103.468 ha de maíz y 97.829 ha de alfalfa, lo que supone un 30% (maíz) y un 66% (alfalfa) de la superficie de regadío de estos cultivos en España (MARM, 2009). Aragón es la comunidad autónoma con mayor superficie de ambos cultivos dentro del Valle del Ebro con 59.547 ha de maíz y 68.012 ha de alfalfa (MARM, 2009). El riego en estas condiciones semiáridas de alta radiación solar permiten obtener altos rendimientos de ambos cultivos (Lloveras y col., 2004; Cavero y col., 2008; Berenguer y col., 2009).

La agricultura ha de permitir, además de obtener unos niveles de productividad elevados, mantener una buena calidad de los recursos suelo y agua, con el fin de tener un desarrollo sostenible y económicamente rentable (CCE, 2002). Existe una preocupación creciente por la contaminación difusa de las aguas superficiales y subterráneas por nitrato debido a sus efectos nocivos sobre la salud de las personas y sobre el medioambiente por la eutrofización de las aguas continentales y costeras (Addiscott y Benjamin, 2004). Esta problemática llevó a la UE a establecer la Directiva 91/676/CEE (transpuesta en España por el Real Decreto 261/1996) y a incluir el nitrato como un indicador de calidad en la reciente Directiva Marco del Agua (2000/60/EC).

Debido a la importancia del maíz y la alfalfa en esta zona, cualquier estrategia para obtener una mayor eficiencia en la utilización del nitrógeno en los sistemas agrarios debe considerarlos a ambos. Si bien la alfalfa es un cultivo que no requiere de la aplicación de fertilizantes nitrogenados, es una entrada significativa de nitrógeno atmosférico a los sistemas agrarios vía fijación simbiótica.

2. Aplicación de purín de cerdo en alfalfa

En el valle del Ebro existe una gran producción ganadera de porcino, con alrededor de 20 millones de cabezas sacrificadas en 2008 (MARM, 2009). Dado el alto contenido en agua del purín porcino su aplicación como fertilizante agrícola suele estar limitada a zonas cercanas al lugar de su producción para que resulte rentable (Yagüe y col., 2008). Esta limitación geográfica puede conducir a la aplicación de dosis excesivas de purín porcino en cultivos extensivos, que ha sido señalada como una de las causas de contaminación por nitratos del agua superficial y subterránea (Daudén y Quílez, 2004; Diez y col., 2004) y de la acumulación de metales pesados en el suelo (L´Herroux y col., 1997; De Temmerman y col., 2003). Los cereales (cebada, maíz y trigo) han sido tradicionalmente los cultivos sobre los que se ha aplicado el purín porcino. Estudios previos indican que la alfalfa puede ser un cultivo alternativo para la aplicación del purín ya que es un cultivo plurianual que permite aplicaciones de purín tanto durante el invierno (Lloveras y col., 2004) como durante el verano (Lamb y col., 2005; Ceotto y Spallacci, 2006). Esto permitiría un incremento tanto de la superficie como de los momentos disponibles para su aplicación, reduciendo las dosis aplicadas por los agricultores a otros cultivos. Si bien es una práctica ya conocida por los agricultores del Valle del Ebro (Sisquella y col., 2004), los estudios sobre la aplicación de purín en alfalfa son escasos y con resultados contradictorios. Algunos trabajos han mostrado resultados positivos (Lloveras y col., 2004; Ceotto y Spallacci, 2006) asociados a un incremento de la fertilidad del suelo (P y K) y del aporte de nutrientes, o negativos (Lamb y col., 2005; Smith y col., 1995), por daños producidos sobre las plantas de alfalfa y por el incremento de la presencia de malas hierbas.

Existe muy poca información sobre las pérdidas de N por lavado tras la aplicación en verano de purín porcino en alfalfa de regadío. Ceotto y Spallacci (2006) observaron contenido bajo de N en el subsuelo tras la aplicación de purín porcino en alfalfa, lo que indicaría un bajo riesgo de pérdidas. Estudios con aplicaciones de purín de vaca en alfalfa de secano han mostrado incrementos significativos de las concentraciones de nitrato en la solución de agua del suelo y en el agua de drenaje (Daliparthy y col., 1994; Toth y col., 2006).

Aunque las pérdidas de P por lavado suelen ser de menor importancia que las de N, las elevadas cantidades de P que se aportan en los purines pueden dar lugar a pérdidas significativas de este elemento (Eghball y col., 1996; Sims y col., 1998). Dado que la mayor parte del Cu y Zn contenidos en los piensos compuestos usados en la alimentación del ganado porcino son excretados por los mismos, la aplicación de altas dosis de purín de cerdo puede dar lugar a la acumulación de metales pesados en el suelo (L´Herroux y col., 1997; De Temmerman y col., 2003). Existe muy poca información sobre estos efectos medioambientales negativos cuando el purín se aplica sobre alfalfa en verano.

3. Utilización de cultivos cubierta en monocultivo de maíz

Las bajas eficiencias de riego y las altas dosis de N aplicadas al maíz han sido identificadas como las causas principales de contaminación por nitrato en los retornos de riego en España (Diez y col., 1997; Cavero y col., 2003; Causapé y col., 2004; Isidoro y col., 2006) y en otras zonas regadas del mundo (Klocke y col., 1999; Pratt, 1984).

Las dosis óptimas estimadas para la fertilización nitrogenada del maíz en los regadíos del Valle Medio del Ebro están situadas entre 0 y 280 kg N ha^{-1}, dependiendo del contenido en N del suelo en el momento de la siembra (Isla y col., 2006; Berenguer y col., 2009). Sin embargo, encuestas a agricultores en zonas del Valle del Ebro indican aplicaciones de 318 - 453 kg N ha^{-1} y año en maíz (Cavero y col., 2003; Isidoro y col., 2006). Esto da lugar a que tras la cosecha de maíz queden en el suelo altos contenidos de N mineral (Cavero y col., 2003; Villar-Mir y col., 2002). Este N residual es susceptible de ser lavado por debajo de la zona de raíces durante el periodo intercultivo (Octubre a Abril) o durante los primeros riegos en el siguiente cultivo de maíz.

Además de las dosis de N fertilizante aplicado, el correcto manejo del riego es un factor clave para reducir las masas exportadas de N con el agua de drenaje en las zonas de riego (Martin y col., 1994; Cavero y col., 2003; Diez y col., 2000). La calidad del riego en condiciones de campo se mide con la eficiencia de riego, que se puede definir como el cociente entre la evapotranspiración del cultivo y la cantidad total de agua aplicada más la precipitación (Howell, 2003). Dependiendo de las propiedades del suelo y del manejo del riego, la eficiencia de riego puede variar desde 53-79% para riego por superficie hasta 94% en riego por aspersión (Causapé y col., 2006). En cuencas de riego del Valle del Ebro se han medido cantidades anuales de N perdido por lavado de 35 a 195 kg ha^{-1} en sistemas de riego por inundación (Causapé y col., 2006;

Isidoro y col., 2006) y de 25 a 50 kg N ha^{-1} en zonas regadas por aspersión (Tedeschi y col., 2001; Cavero y col., 2003).

Se denominan cultivos cubierta (o captura) a aquellos que se utilizan en el periodo intercultivo de un cultivo principal con el fin de disminuir la lixiviación de nitratos (Thorup-Kristensen y col., 2003). Los cultivos cubierta absorben el nitrógeno mineral residual en el suelo tras la cosecha del cultivo anterior y el mineralizado durante el periodo intercultivo, evitando de este modo la pérdida de este nitrógeno por lavado. Al final del periodo intercultivo, el nitrógeno absorbido por los cultivos cubierta se puede exportar fuera del sistema o se puede incorporar al mismo como un abono verde para que sea utilizado por los siguientes cultivos después de su mineralización. Por esta razón han sido considerados como herramientas medioambientales que mejoran la sostenibilidad de los sistemas agrarios, ya que permiten un reciclado del nitrógeno excedentario del sistema, reduciendo el impacto ambiental al controlar la lixiviación de nitrato (Wagger y Mengel, 1988, Dinnes y col., 2002). Los cultivos cubierta presentan además otros beneficios, como son el control en la erosión del suelo y mejora de la estructura, control de malas hierbas, plagas y patógenos del suelo (Thorup-Kristensen y col., 2003).

El uso de cultivos cubierta durante el periodo intercultivo de maíz (Octubre-Marzo) puede minimizar las concentraciones y masas de nitrato del suelo y por lo tanto de las aguas de drenaje. Los efectos positivos de esta práctica han sido estudiados en zonas húmedas de EEUU (McCracken y col., 1994; Brandi-Dohrn y col., 1997; Isse y col., 1999; Rasse y col., 2000; Tonitto y col., 2006), Canadá (Ball-Coello y col., 2004) y del norte de Europa (Martínez y Guiraud, 1990). Estos estudios se han realizado en zonas de alta pluviometría, pero la información es limitada para las condiciones semiáridas del clima Mediterráneo. Existen estudios realizados en zonas de agricultura de regadío en los que se recomienda el uso de cultivos cubierta durante el invierno en rotaciones de cultivos hortícolas (Shennan, 1992; Poudel y col., 2001; Snapp y col., 2005), pero hay poca información disponible sobre su uso en monocultivo de maíz.

Los cereales utilizados como cultivos cubierta a menudo tienen un efecto nulo o negativo en el rendimiento del cultivo de maíz posterior comparados con un tratamiento control con suelo desnudo durante el invierno (Martinez y Guiraud, 1990; Kuo y Jellum., 2000; Holderbaum y col., 1990; Miguez y Bollero, 2005, 2006). En cambio, los cultivos cubierta de leguminosas suelen incrementar el rendimiento del maíz (Holderbaum y col., 1990; Kuo y Jellum., 2000; Kuo y col., 1996; Decker y col., 1994; Utomo y col., 1990; Miguez y Bollero., 2005, 2006).

Una de las dificultades para el desarrollo de los cultivos cubierta en el valle medio del Ebro es la limitación de tiempo después de la cosecha de maíz antes de que lleguen las bajas temperaturas. Estas bajas temperaturas condicionan el establecimiento del cultivo cubierta, su acumulación de biomasa y el N absorbido (Diez y col., 1997). Por este motivo es esencial evaluar distintos cultivos cubierta y su correcta implantación en las condiciones del Valle medio del Ebro. La utilización de sistemas de siembra directa tras la cosecha del maíz puede permitir adelantar la fecha de siembra de los cultivos cubierta facilitando su implantación, pero también afectar a la descomposición de los residuos de maíz (Dorsainvil y col., 2005).

La baja precipitación invernal (<200 mm) del Valle del Ebro hace que las pérdidas de N se produzcan sobretodo durante la estación de riego (Cavero y col., 2003; Causapé y col., 2006), dificultando el adoptar recomendaciones para maíz cultivado en zonas más húmedas. Una hipótesis razonable es que el uso de cultivos cubierta puede reducir el N residual en el suelo, disminuyendo las pérdidas de N por lavado durante el invierno y durante el inicio de la estación de riego.

4. Modelización del uso de cultivos cubierta en monocultivo de maíz.

La utilización de modelos capaces de simular el crecimiento de los cultivos cubierta, su descomposición y los efectos en el siguiente cultivo de maíz puede ser una herramienta muy útil para estudiar la aplicabilidad de los cultivos cubierta para reducir el lavado de N en distintos escenarios. Una vez validados, los modelos pueden ser utilizados para estudiar distintas estrategias de manejo (Kovacs y col., 1995; Boote y col., 1996.; Royce y col., 2001., Ruiz-Nogueira y col., 2001; Jagtap y Abamu, 2003).

El modelo DSSAT (Decission Support System for Agrotechnology Transfer, Tsuji y col., 1994) se ha utilizado para estudiar el manejo de distintos cultivos en un amplio rango de climas y condiciones. DSSAT incorpora el modelo CERES-Maize para realizar las simulaciones del cultivo de maíz, que ha dado buenos resultados tanto en condiciones de cultivo sin riego (Paz y col, 1999; Pang y col, 1998; Keating y col.; 1991) como en condiciones de cultivo bajo riego en clima semiárido (Carberry y col., 1989; Gerçek y Okant, 2010). Sin embargo, existe poca información sobre su uso en sistemas de cultivo que incluyen cultivos cubierta. Cabe destacar las simulaciones realizadas por Bowen y col. (1993) con rotaciones con cultivos cubierta leguminosos en maíz.

El modelo CENTURY que simula las transformaciones de la materia orgánica del suelo (Parton y col., 1994) fue adaptado para su incorporación a DSSAT (Gijsman y col., 2002). Este modelo es capaz de simular con exactitud procesos largos de transformación de la materia orgánica en el suelo (Kelly y col., 1997; Smith y col., 1997), pero la mayor parte de los estudios tratan de procesos de mineralización del carbono, y menos del nitrógeno. Es necesario conocer el comportamiento del modelo DSSAT-Century para simular la mineralización de los cultivos cubierta en las condiciones de regadío y clima semiárido del Valle del Ebro.

Antes de utilizar el modelo como herramienta para extrapolar los resultados experimentales es necesario examinar la exactitud del modelo para simular el ciclo del N en un rango de climas y condiciones de manejo (Carberry y col., 1989; Castignano y col., 1998.; du Toit y col., 2002.; Ben Nouna y col., 2003; Lopez-Cedrón y col., 2008). Los ensayos realizados con rotaciones de cultivos cubierta en monocultivo de maíz en las condiciones bajo riego y clima semiárido del Valle del Ebro pueden ser una buena base de datos para determinar la capacidad del modelo para simular con exactitud la mineralización del N de los cultivos cubierta y su disponibilidad para el cultivo siguiente en estas condiciones.

5. Objetivos

Con el fin de establecer distintas estrategias para optimizar el uso del N en cultivos extensivos de regadío del Valle del Ebro, la tesis se desglosa en cuatro apartados, cada uno de los cuales tiene sus objetivos específicos, que se detallan a continuación:

5.1. Aplicación de purín porcino durante el periodo de crecimiento de la alfalfa. Efectos sobre el rendimiento de la alfalfa y sobre el medioambiente.

Objetivos: Cuantificar los efectos de aplicaciones de purín durante el periodo de crecimiento de alfalfa en cuanto (1) al rendimiento y calidad del forraje, (2) a la cantidad de N y P lavado, y (3) a la acumulación de N inorgánico, P, y metales pesados (Cu y Zn) en el suelo.

5.2. Efecto de los cultivos cubierta en las pérdidas por lavado de N y en el rendimiento de maíz.

Objetivos: Estimar el efecto de distintos cultivos cubierta en un monocultivo de maíz en cuanto (1) a la concentración y masa de nitrato en el agua de drenaje medidos en lisímetros de drenaje y (2) al rendimiento de maíz cultivado posteriormente.

5.3. Influencia del sistema de implantación y de la especie de cultivo cubierta en la evolución del contenido de N en el suelo y en el rendimiento de maíz.

Objetivos: Evaluar el efecto del sistema de siembra y de la especie del cultivo cubierta en un monocultivo de maíz en cuanto (1) a la producción de biomasa y el contenido de N de los cultivos cubierta, (2) al contenido del suelo en N inorgánico y agua, y (3) al rendimiento del cultivo de maíz posterior.

5.4. Aplicabilidad del modelo de simulación DSSAT para simular el ciclo del N en rotaciones de cultivos cubierta-maíz bajo condiciones de regadío en clima semiárido.

Objetivos: Evaluar el modelo DSSAT en rotaciones de cultivos cubierta-maíz para simular (1) el rendimiento de maíz tras cultivos cubierta, (2) el ciclo del N, (3) la temperatura del suelo, y (4) el efecto de los cultivos cubierta sobre el lavado de nitrato y el rendimiento de maíz en una cuenca de regadío del Valle Medio del Ebro.

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Capítulo 2

Yield and environmental effects of summer pig slurry applications to irrigated alfalfa under Mediterranean conditions

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Waste Management

Yield and Environmental Effects of Summer Pig Slurry Applications to Irrigated Alfalfa under Mediterranean Conditions

Montserrat Salmerón,* José Cavero, Ignacio Delgado, and Ramón Isla

ABSTRACT

In the Ebro Valley (Spain), the intensive pig (*Sus scrofa*) production combined with a limited nearby cereal growing area for spreading pig slurry residue is leading more farmers to apply slurry to alfalfa (*Medicago sativa* L.). The effects of summer pig slurry applications on irrigated alfalfa yield and the environment have not been adequately established. An experiment was conducted in 12 drainage lysimeters in 2007 and 2008, where two rates of pig slurry (low (LD), 140 kg N ha^{-1} yr^{-1}; high (HD) 340 kg N ha^{-1} yr^{-1}) were compared to a P-K fertilized control. Application of pig slurry did not affect accumulated forage yield after 2 yr (37.3 Mg ha^{-1}). Forage N concentration and total N extractions (1214 kg ha^{-1}) were similar for all treatments, revealing a high flexibility of the crop to adjust symbiotic N fixation depending on mineral N availability. The NO_3^-–N and P concentrations and loads in drainage were very low (< 2 kg N ha^{-1} yr^{-1} and 0.035 kg P ha^{-1} yr^{-1}) and not affected by the pig slurry applications. Soil P in the surface layer (0–0.3 m) increased by a 19% as a result of both pig slurry and P fertilization. Application of pig slurry did not significantly increase the Zn and Cu content of the soil. These results indicate the feasibility of moderate pig slurry applications to growing alfalfa in the Ebro Valley, which will improve the management of this residue.

Animal manure is a source of N and other nutrients when applied to crops, being a cost-effective way to dispose this animal waste. Manure is most often applied to nonleguminous crops such as maize (*Zea mays* L.), where the effects of its application have been widely studied (Eghball and Power, 1994; Daudén and Quílez, 2004). Among the different types of manures, pig slurry has a more limited geographical application area due to its high water content, which makes it uneconomical to apply it far away from hog farms. Therefore, in those areas where swine production is the main agricultural activity, the high density of farms results in applications of excessive rates of pig slurry to cereal fields. This can lead to surface and groundwater nitrate pollution (Daudén and Quílez, 2004; Diez et al., 2004) and heavy metal accumulation in soil (L'Herroux et al., 1997; De Temmerman et al., 2003).

Alfalfa can be an alternative crop for slurry applications, as it is a perennial forage that allows winter applications in established stands (Lloveras et al., 2004), as well as mid-summer applications after forage cuts (Lamb et al., 2005; Ceotto and Spallacci, 2006). This can enable an increase of the land and time available for pig slurry management, but the reported effects of this practice on alfalfa yield are limited and variable. Winter applications of pig slurry in established alfalfa increased forage yield in low fertility soils due to the P and K supplied with the slurry (Lloveras et al., 2004). In contrast, Lamb et al. (2005) reported detrimental effects on summer yields with rates above 3300 kg ha^{-1} of total slurry solids, due to a possible smothering effect of a slurry coating on the alfalfa vegetation. Other studies on dairy slurry (Smith et al., 1995) indicate that a combination of soil compaction by slurry application equipment and the increase of weed occurrence are the main causes of the detrimental effect of this practice on alfalfa yield. On the other hand, Ceotto and Spallacci (2006) observed positive effects of pig slurry on alfalfa yield, which attributed to a reduction in energy costs for sustaining root nodules and symbiotic organisms compared to the energy requirement for nitrate reduction (Loomis and Connor, 1992). It has been reported that even though alfalfa can obtain N through symbiotic fixation, the crop can benefit from N fertilization (Raun et al., 1999).

From a social viewpoint, the environmental effects of pig slurry management are even more relevant than the effects on crops. In Spain, the agricultural areas with higher N contamination in surface water have been associated with irrigated crops with high N demand such as maize (Diez et al., 1997; Cavero et al., 2003; Causape et al., 2004; Isidoro et al., 2006). However, information reporting N loads in drainage after summer application of pig slurry in an established irrigated alfalfa crop is not available. Ceotto and Spallacci (2006) reported low subsoil N contents after pig slurry applications, thus entailing low N leaching risks. Studies with dairy slurry (Daliparthy et al., 1994) and dairy manure (Toth et al., 2006) applications to alfalfa under rainfed conditions found significant increases in soil water nitrate concentration and N loads in drainage with moderate to high doses of slurry (177–340 kg N ha^{-1}).

M. Salmerón and R. Isla, Unidad de Suelos y Riegos (asociada al CSIC), Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA), Gobierno de Aragón, Avda. Montañana 930, 50059 Zaragoza, Spain; J. Cavero, Dep. Suelo y Agua, Estación Experimental de Aula Dei (CSIC), Avda. Montañana 1005, 50059 Zaragoza, Spain; I. Delgado, Unidad de Producción Animal, Centro de Investigación y Tecnología Agroalimentaria de Aragón (CITA), Gobierno de Aragón, Avda. Montañana 930, 50059 Zaragoza, Spain. Received 18 Sept. 2009. *Corresponding author (msalmeronc@aragon.es).

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Abbreviations: CT, control treatment; HD, pig slurry high dose; LD, pig slurry low dose.

Leaching of P from agricultural areas has generally not been considered a big concern because of the high P-fixation capacity in many mineral soils (Sims et al., 1998). Surface runoff losses is the main mechanism of P losses in agricultural fields. However, recent studies (Eghball et al., 1996; Sims et al., 1998; Brye et al., 2002) indicate that significant risk of soil P leaching exists under some conditions, such as in soils with a coarse texture and/or preferential water flows, or after heavy long-term manure applications.

Minerals such as Cu and Zn are added to pig diets as growth promoters or mineral supplements (Underwood and Suttle, 1999). Pigs use these elements poorly, and most of the Cu and Zn added is lost in feces and urine (Nicholson et al., 2003). As a result, intensive use of pig slurry as a fertilizer can lead to accumulation of heavy metals in the soil (L'Herroux et al., 1997; De Temmerman et al., 2003). Concern over soil pollution risks from this practice prompted stricter policies in Europe (EC 1334/2003) which have reduced the maximum levels of these elements in swine diets.

In the Ebro Valley (Spain), alfalfa is one of the main irrigated crops (about 120,000 ha) (MARM, 2008) due to its high productivity (up to 20 Mg ha^{-1} yr^{-1} in 6–7 cuts) and forage quality. The Ebro Valley is also a main swine production area with about 18 million pigs (MARM, 2008). Nowadays, due to the urgent need for land area and disposal time, pig slurry is being applied to irrigated alfalfa by 30% of farmers in the region (Sisquella et al., 2004). Therefore, the impact on the environment of pig slurry applications to alfalfa should be assessed under the conditions of this agricultural area, where alfalfa is grown under irrigation. To our knowledge there is no information about the N and P leaching after application of pig slurry in an established irrigated alfalfa crop.

Therefore, the objectives of our experiment were to assess the effects of summer pig slurry applications to an irrigated growing alfalfa crop on: (i) the total dry matter and quality of alfalfa forage, (ii) the nitrate and P leached, and (iii) the accumulation of inorganic N, P, and heavy metals in the soil.

MATERIALS AND METHODS

Site and Experimental Design

The experiment was performed during the 2006 to 2008 alfalfa growing seasons at the CITA experimental station located in the Ebro Valley (41°44′ N, 0°49′ W) in Spain. Twelve drainage lysimeters of an area of 5.2 m^2 and 1.5 m depth were used. The lysimeters were filled 10 yr before the experiment with the upper horizons of a nearby silt loam soil. The soil had 23% of sand, 51% of silt and 26% of clay, a 0.37 m^3 m^{-3} water content at field capacity (–0.033 MPa) and 0.17 m^3 m^{-3} water content at wilting point (–1.5 MPa). This is a calcareous soil with a $CaCO_3$ equivalent of 326 g kg^{-1}, a pH of 8.2 (water), and an organic mater content of 22 g kg^{-1} in all the lysimeter depth. Crops previous to the start of the experiment were maize (2001–2004) and 1 yr (2005) of unfertilized sunflower (*Helianthus annuus* L.). Weather data were obtained from a nearby automatic weather station. Mean annual air temperature and total annual precipitation were 14.8, 13.9 and 13.9°C, and 323, 359, and 451 mm in 2006, 2007, and 2008, respectively.

Alfalfa cultivar Aragon seeds were inoculated with *Rhizobium melioti* to ensure sufficient and uniform nodule formation in all lysimeters. Alfalfa was sown on 26 Apr. 2006 at a seeding rate of 30 kg ha^{-1}. The soil was fertilized prior planting with 30 kg ha^{-1} N, 200 kg ha^{-1} P_2O_5 and 200 kg ha^{-1} K_2O. During the first growing season (2006) no further fertilization was applied. The treatments started in the second growing season (2007) and continued during the third growing season (2008). Three different treatments were evaluated: (i) a control treatment (CT) without pig slurry applications but with P-K fertilizer supplied in February at 200 kg ha^{-1} yr^{-1} P_2O_5 and 150 kg ha^{-1} yr^{-1} K_2O; (ii) a low dose treatment (LD) consisting in a pig slurry rate equivalent to 170 kg N ha^{-1} yr^{-1}; and (iii) a high dose treatment (HD), equivalent to 340 kg N ha^{-1} yr^{-1}. The experiment consisted of a complete randomized design with four replicates (lysimeters). Pig slurry was surface applied and split into two applications, after the first (end of April) and third (end of June) alfalfa cuts. The lysimeters were immediately irrigated to minimize smothering effects on the crop and N losses by volatilization. Alfalfa was irrigated once or twice a week, depending on water needs, using a dense drip irrigation system that simulated flood irrigation (average flow of 48 L m^{-2} h^{-1}). The irrigation requirement was calculated from the reference evapotranspiration (estimated with the Penman–Monteith equation) and the crop coefficients, according to the FAO procedures (Allen et al., 1998) and considering a leaching fraction of 15%. The volume of irrigation water applied in each irrigation was measured with a flow meter (MFSM 25, Hidroconta, Murcia, Spain).

Liquid pig slurry was collected from a nearby farm, stored in a closed tank, and agitated before application to homogenize its composition. Pig slurry was manually applied over the soil surface of each lysimeter using a watering can. Ammonia N was determined in the field with a Quantofix N meter (Piccinini and Bortone, 1991). The volume of pig slurry to be applied in each treatment was calculated on the basis of its total N content, assuming that ammonia N comprises 75% of the total N of the slurry. The actual volumes of pig slurry applied each year were 96 and 44 m^3 ha^{-1} in the HD treatment, corresponding to 354 and 403 kg N ha^{-1} in 2007 and 2008, respectively (Table 1). Half of these rates were applied in the LD treatment. These amounts were 4% (2007) and 18% (2008) higher than the target rates (170 kg N ha^{-1} yr^{-1} in the LD and 340 kg N h^{-1} yr^{-1} in the HD).

A sample of the slurry used at each application was frozen for later analyzing its chemical composition. Organic and ammonium N contents were analyzed by Kjeldahl method (Nelson and Sommers, 1973). After digestion with nitric and hydrochloric acid the P, Ca, Mg, Fe, Cr, Pb, Zn, Cd, Ni, and Cu contents were analyzed by inductively argon plasma spectrophotometry (Iris Advantage Ers Duo, Thermo-Optek, Krankling, MA). The chemical composition of pig slurry is presented in Table 2.

Plant, Water, and Soil Analysis

Alfalfa was cut four times in 2006 and seven times in 2007 and 2008. Forage cuts were done at about 10% blooming stage. In 2008, the fourth cut was lost due to a hailstorm. At each cut, forage biomass from 1 m^2 was harvested at 8 cm from the surface in each lysimeter and weighed. A subsample was oven dried at 65°C to determine the dry weight and ground for nutrient analyses. Total N of biomass was analyzed by the combustion method with a CN analyzer (TruSpec CN, LECO, St. Joseph, MI), and mineral elements and heavy metals were determined by inductive argon plasma spectrophotometry (Iris Advantage Ers Duo,Thermo-Optek, Krankling, MA) after digestion with nitric and hydrochloric acid. Relative air abundance of N isotopes ($\delta^{15}N$) in alfalfa tissues and in the slurry was measured by mass spectrometry (DELTA^{plus}, Finnigan MAT, Scientific Instruments Services Inc., NJ). The $\delta^{15}N$ of plants usually reflects the source of N (Choi et al., 2003; Lim et al., 2007; Senbayram et al., 2008). To determine the percentage of N in alfalfa forage that comes from atmospheric N_2 fixation is necessary to analyze $\delta^{15}N$ of alfalfa forage and in addition the $\delta^{15}N$ of a reference plant that does not uptake atmospheric N_2 by fixation. This could be a non-nodulating alfalfa or another plant species that do not uptake N by fixation. Methodological problems have been pointed out about the use of reference plants (Houngnandan et al., 2008). Moreover, in our experiment the small size of the lysimeters precluded the use of a reference crop. The comparison of $\delta^{15}N$ alfalfa forage between the different treatments was used to detect qualitative changes in the source (atmospheric N fixation or pig slurry) of N uptake by the alfalfa crop. This comparison has been successfully used to determine the origin of N uptake from organic manures, soil, and synthetic fertilizers (Choi et al., 2003; Lim et al., 2007).

Water drainage from each lysimeter was collected in 50 L tanks, set in an underground room. Drainage volume was measured on a weekly basis, and a sample of 100 mL was collected from each lysimeter. Electrical conductivity (EC) of drainage water was measured with an EC meter (CDM 83, Radiometer Copenhagen, Denmark) and the NO_3^-–N and NH_4^+–N concentrations were determined colorimetrically with a continuous flow analyzer (AA3, Bran+Luebbe, Norderstedt, Germany). Another drainage water subsample of 200 mL was frozen and total P was later determined by spectrometry UV-VIS (following UNE-EN 1189) (SPECORD 250, Analytik Jena AG, Jena, Germany) after digestion with sulfuric and nitric acid. For dissolved P quantification, the sample was previously filtered with a cellulose filter (GF52 047, Albet-hahnemuehle, Barcelona, Spain) of 0.45 μm pore size, free of P and previously washed. Average monthly concentrations of NO_3^-–N, NH_4^+–N and P in drainage were calculated by weighing the weekly concentration values with the weekly drainage volumes.

Soil was sampled before alfalfa sowing (6 Apr. 2006), at the start of the second growing season (February 2007), and at the end of each of the two growing seasons when the slurry was applied (16 Nov. 2007 and 5 Nov. 2008). Two replicated samples were combined into one bulk sample for each lysimeter and soil layer. The soil was sampled to 1.2 m depth in 0.3 m increments. The soil was fresh sieved to pass 2 mm, and 10 g were extracted with 2 mol L^{-1} KCl for determining NO_3^-–N and NH_4^+–N concentrations by the same procedure cited above. Soil inorganic N (N_{inorg}) was determined as the sum of NO_3^-–N and NH_4^+–N concentrations. In the last soil sampling, P (Olsen), Cu, and Zn contents were determined in air-dried and ground soil samples by inductive argon plasma spectrophotometry (Iris Advantage Ers Duo,Thermo-Optek, Krankling, MA).

Table 1. Volume of pig slurry applied and total amount of N, P, and K applied and removed by the alfalfa forage in the different treatments during the 2007 and 2008 growing seasons.

Year and treatment	Pig slurry volume	Pig slurry and fertilizer N	P	K	Forage removal† N	P	K
	m^3 ha^{-1}	kg ha^{-1}					
2007							
Control	–	–	200	150	660 b	64 ab	564 b
Pig slurry low dose	48	177	63	68	685 a	66 a	590 a
Pig slurry high dose	96	354	126	137	646 b	61 b	563 b
2008							
Control	–	–	200	150	540	54	473
Pig slurry low dose	22	201	40	90	570	58	503
Pig slurry high dose	44	403	81	181	544	55	484

† For each year/variable group, means having the same letter in common are not significantly different at the 5% level of significance as indicated by Fisher's Protected LSD test. The absence of letters within a group indicates that the treatment effect was nonsignificant in the ANOVA.

Statistical Analysis

The statistical analyses were performed using the SAS 9.1 software (SAS Institute, 2004). Yield and soil data were analyzed with analysis of variance using the proc General Linear Model (GLM) and multiple comparisons were performed using Fisher's Protected LSD test at $P = 0.05$. For repeated measures over time, such as drainage data, alfalfa yield, and ^{15}N natural abundance ($\delta^{15}N$), the MIXED procedure was used taking into account an autoregressive covariance structure for the data.

RESULTS

Forage Yield and Quality

Alfalfa yields were within standard values for irrigated alfalfa in the region (Delgado et al,. 2006), with average values of 13.0 Mg ha^{-1} in the establishment year, and 20.5 and 16.9 Mg ha^{-1} in the two subsequent years (2007 and 2008) (Table 3), when the pig slurry treatments were conducted. The lower yields obtained in 2008 were due to the loss of the fourth cut due to a hailstorm. Alfalfa yield was significantly higher in the LD treatment in 2007, with an increase of 1.3 and 0.9 Mg ha^{-1} compared to the HD and CT treatments, respectively (Table 3). In the following year, although no significant differences were found among the different treatments, application of pig slurry at the lower rate resulted in 1 Mg ha^{-1} more forage than the other treatments. Total alfalfa yield after 2 yr of pig slurry applications (2007 and 2008) was not affected by the treatments. The analysis of harvest yields over time did not reveal a significant treatment effect or a cut × treatment interaction.

Nutrient analysis in the alfalfa forage (Table 3) showed no differences for the macronutrient concentrations (N–P–K), but significant differences were found for some micronutrients and

Table 2. Chemical composition of the pig slurry applied in 2007 and 2008 (dry matter basis).

Application date	pH	Dry matter	NH_4^+–N	Total N	P	K	Ca	Mg	Fe	Zn	Cu	$\delta^{15}N$
		g kg^{-1}								mg kg^{-1}		‰
16 Apr. 2007	7.8	111	2.60	4.54	1.81	1.43	2.81	0.81	0.15	1.23	0.65	11.7
25 June 2007	8.4	26	6.61	9.48	2.76	4.63	3.64	1.28	0.30	3.38	1.04	5.6
24 Apr. 2008	8.2	145	3.32	5.51	1.57	2.70	3.34	1.22	0.19	3.67	0.34	10.5
25 June 2008	8.0	82	8.65	10.80	1.24	4.43	2.77	1.03	0.14	2.00	0.29	8.1

Table 3. Alfalfa forage yield and chemical composition in the different treatments during the 2007 and 2008 growing seasons.

Year and treatment	Forage														
	Yield†	N	P	K	Ca	Mg	S	B	Cu	Fe	Mn	Na	Zn	Mo	Cr
	$Mg\ ha^{-1}$	%						$mg\ kg^{-1}$							
2007															
Control	20.3 b	3.25	0.32	2.78	1.84	0.22	0.40	52.9	10.4 b	175	19.4	2642 a	33.9	2.94	1.13
Pig slurry Low Dose	21.2 a	3.26	0.31	2.84	1.83	0.22	0.41	52.2	10.9 b	169	19.3	2605 ab	36.8	3.19	1.09
Pig slurry High dose	19.8 b	3.23	0.31	2.78	1.84	0.23	0.41	52.6	11.7 a	178	18.8	2449 b	37.3	3.01	1.15
2008															
Control	16.5	3.28	0.33	2.87	2.04	0.24 b	0.40	62.2	12.1	243	25.1	3850	30.4 b	2.36 b	1.27
Pig slurry Low Dose	17.6	3.28	0.33	2.92	2.07	0.26 a	0.41	59.9	12.4	254	23.8	3792	34.8 ab	2.71 a	1.52
Pig slurry High dose	16.6	3.24	0.33	2.86	2.10	0.26 a	0.41	58.6	12.6	248	24.1	3527	36.7 a	2.87 a	1.46

† For each year/variable group, means having the same letter in common are not significantly different at the 5% level of significance as indicated by Fisher's Protected LSD test. The absence of letters within a group indicates that the treatment effect was non-significant in the ANOVA.

heavy metals in the LD and HD treatments compared to the CT. In 2007, Cu concentration increased as a result of the pig slurry applications. In 2008, Mg, Zn, and Mo concentrations increased with increasing rates of pig slurry. On the other hand, Na concentrations showed a different tendency, with slightly higher contents in the CT compared to the LD and HD treatments in 2007. Accumulated uptake of N and K in the alfalfa forage were significantly higher in the LD treatment in 2007 (Table 1), linked to the higher yields in this treatment. After 2 yr of pig slurry application, the mean uptake of N, P, and K were 611, 60, and 529 kg ha^{-1} yr^{-1}, respectively, without a significant treatment effect.

The $\delta^{15}N$ in the applied slurry ranged from 5.6 to 11.7 $^0/_{00}$ (Table 2). These are lower than the values reported by Lim et al. (2007), averaging $16^0/_{00.}$ The $\delta^{15}N$ values can be variable, as they are likely to increase with ammonia volatilization processes (Choi et al., 2003). Initial values for $\delta^{15}N$ in the alfalfa forage were similar in all treatments before the start of the pig slurry applications (2007, first cut) and were maintained at relatively low values throughout the experiment in the CT (average of $1.2^0/_{00}$) (Fig. 1). However, after the first pig slurry application, values of $\delta^{15}N$ increased significantly in the LD and HD treatments compared to the CT, with peak differences in the forage cuts following each slurry application and decreasing by the end of the growing season. In the first cut in 2008, $\delta^{15}N$ values were lower in the LD treatment compared to the CT, but after the pig slurry application, $\delta^{15}N$ increased again in the slurry treatments compared to the CT, although information from the fourth cut was lost due to a hailstorm. The mean values of $\delta^{15}N$ across the two growing seasons were $1.2^0/_{00}$, $1.8^0/_{00}$, and $2.8^0/_{00}$ for the CT, LD, and HD treatments, respectively.

Drainage Water Volume and Quality

The volume of drainage was not affected by the pig slurry applications (Fig. 2)., averaging a total of 803 mm from 2006 to 2008 in the 12 lysimeters. The average leaching fractions obtained were 19, 14, and 14% for the three growing seasons (2006–2008), close to the target leaching fraction of 15%. Drainage events occurred from the start of irrigation in April to the end of the growing season, but no drainage was observed during the autumn and winter period, due to scarce precipitation.

In 2007, the monthly average EC of drainage water was not affected by the pig slurry treatment (Fig. 3). However, the annual average was significantly higher ($P = 0.053$) in the HD treatment (7.0 dS m^{-1}) compared to the LD (5.8 dS m^{-1}) and the CT treatments (5.6 dS m^{-1}). In 2008, the July and August average EC of drainage water was higher in the HD than in the CT (Fig. 3). This year the annual average was higher in the HD (8.1 dS m^{-1}) compared to the LD (6.9 dS m^{-1}) and CT (6.0 dS m^{-1}) treatments, being higher in the LD than in the CT treatment.

The maximum NO_3^-–N concentration in drainage water was observed during the establishment year of alfalfa with average monthly values of 20 mg L^{-1} in April. From April to October 2006, nitrate concentration decreased linearly over time to concentrations below 5 mg L^{-1} NO_3^-–N (Fig. 4). The low NO_3^-–N concentrations in drainage water were maintained during the two subsequent years and were not affected by slurry application rates. In 2008, nitrate concentrations were in some dates below the analysis detection limit (0.1 mg L^{-1} NO_3^-–N). Statistical analysis of nitrate concentrations did not show significant differences between treatments.

Pig slurry contains a significant amount of ammonium and P (Table 1). Thus, the temporal evolution of NH_4^+–N (Fig. 5), and soluble and total P in drainage water (Fig. 6) were analyzed. Ammonium

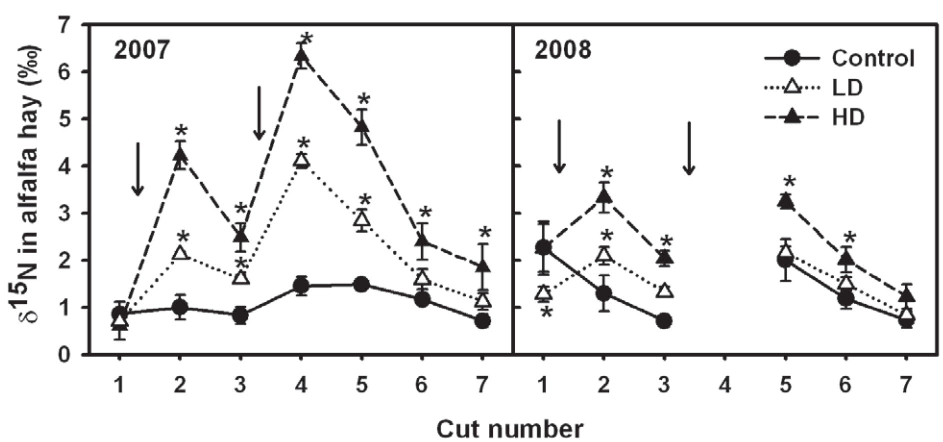

Fig. 1. Evolution of the $\delta^{15}N$ in the alfalfa forage during the 2007–2008 growing seasons for the control, pig slurry low dose (LD), and pig slurry high dose (HD) treatments. The arrows indicate the dates of slurry application. Vertical bars indicate the standard error ($n = 4$). * Indicate significant differences ($P < 0.05$) compared to the control treatment for a given cut.

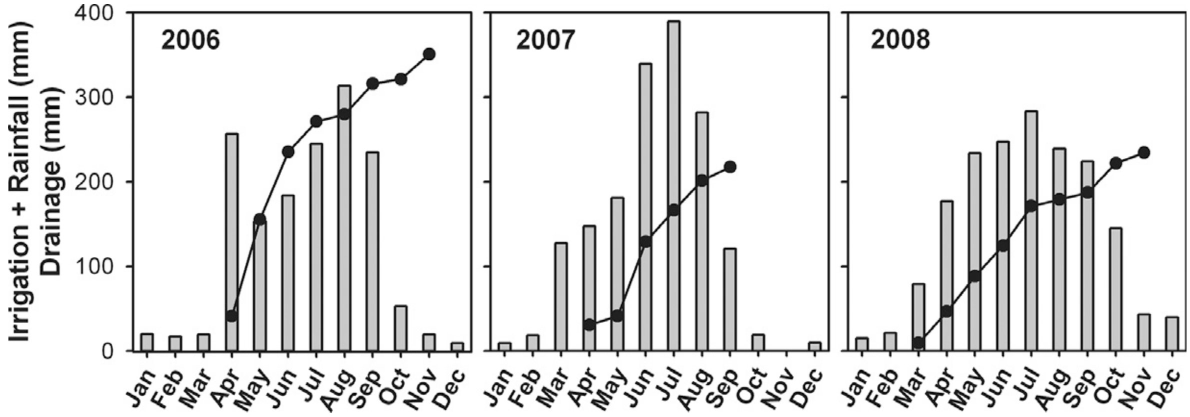

Fig. 2. Monthly distribution of irrigation + rainfall (vertical bars) and cumulative volume of drainage collected from the lysimeters (closed circles) during the 3 yr of the experiment.

concentration was always lower than 1.6 mg L^{-1} and was not affected by the slurry treatments in the two growing seasons. Concentrations of soluble and total P in drainage water were also not significantly different between the treatments studied, ranging from below the detection limit of 0.001 mg L^{-1} to a maximum of 0.040 and 0.051 mg L^{-1} of soluble and total P, respectively. Total P concentrations exceeded the threshold level for eutrophication of 0.02 mg L^{-1} (Sharpley and Rekolainen, 1997) in 6% of the drainage events in 2007, and in 26% in 2008.

The total mass of NO_3^-–N leached averaged 46 kg ha^{-1} in the establishment year of alfalfa (2006). However, during the two following years when the treatments were conducted, the mass of NO_3^-–N leached was only 1.7 kg N ha^{-1} (2007) and 0.7 kg N ha^{-1} (2008) with no effect of the pig slurry applications. The mass of NH_4^+–N leached in 2008 was very low, with 0.9 kg ha^{-1} lost. Total P leached, measured after the first pig slurry application in 2007, averaged 26 and 44 g ha^{-1} in 2007 and 2008, without significant differences between treatments. Most of the P in drainage was in a soluble form, with particulate P comprising a 19 and 35% of total P in 2007 and 2008, respectively.

Nitrogen, Phosphorus, and Heavy Metals Accumulation in the Soil

Soil inorganic N content in the 0- to 1.2-m depth soil profile at the start of the experiment (spring 2006) was 144 kg ha^{-1}, and decreased to 74 kg ha^{-1} in spring of the following year (2007) (Fig. 7a). This decrease occurred in all the soil profile and reflects the deep rooting of alfalfa. At the end of the growing seasons 2007 and 2008, the soil inorganic N content averaged 143 and 103 kg N ha^{-1}, with no significant differences among the treatments studied (Fig. 7b-c).

Initial values (2006) of available soil P (Olsen) in the 0- to 0.3-m soil layer averaged 33.0 mg kg^{-1} of P (CV = 13%) and at the end of the experiment had increased to 39.9 (CV = 8%), without differences between treatments (Table 4). Soil Cu and Zn content did not show a significant ($P > 0.05$) effect of the pig slurry applications, however average Zn soil content in the 0- to 0.3-m soil layer were 17% higher in the pooled pig slurry treatments compared to the CT (Table 4).

DISCUSSION

Forage Yield and Quality

Other research under similar management and climatic conditions found potential benefits of winter pig slurry applications on alfalfa yield under P deficient soils (Lloveras et al., 2004). In the high fertility soil of our study, forage yield only had a slight increase with pig slurry LD application in one of the 2 yr compared to the P–K fertilized control. Moreover, the similar total forage yield after 2 yr in the control treatment and

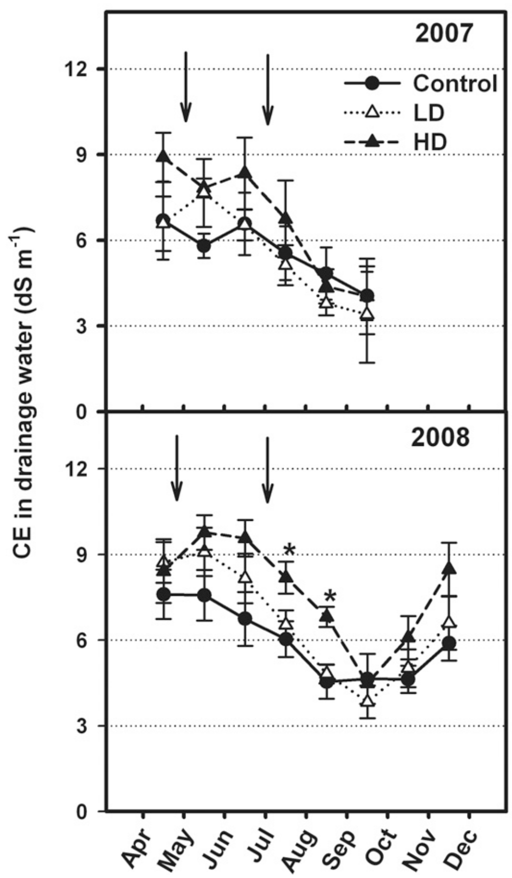

Fig. 3. Monthly average electrical conductivity (EC) in drainage water in the different treatments (control, pig slurry low dose (LD), and pig slurry high dose (HD)) during 2007 and 2008. The arrows indicate the dates of slurry application. Vertical bars indicate the standard error (*n* = 4). * Indicate significant differences (*P* < 0.05) compared to the control treatment within monthly averages.

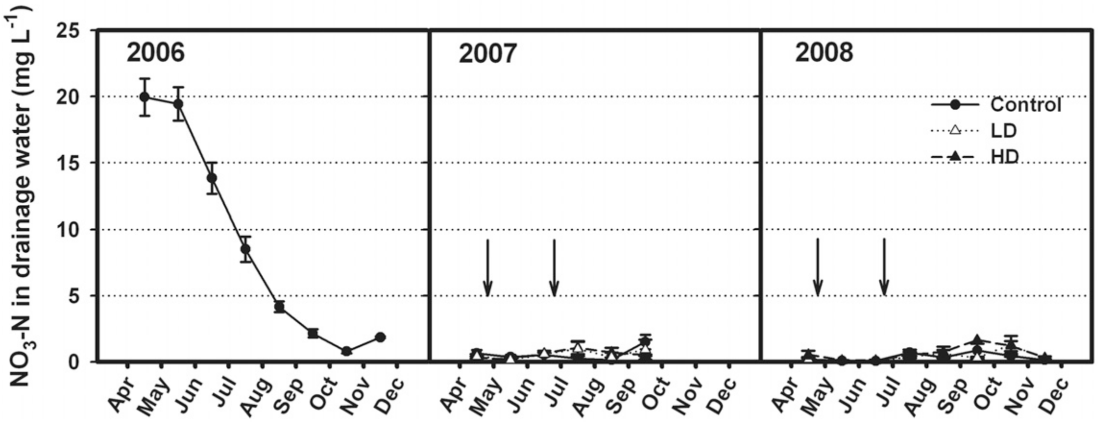

Fig. 4. Monthly average NO_3–N concentration in drainage water in the different treatments (control, pig slurry low dose [LD], and pig slurry high dose [HD]) during 2007 and 2008. Data of 2006 are the average of 12 lysimeters. The arrows indicate the dates of slurry application. Vertical bars indicate the standard error.

the pig slurry treatments did not show the yield benefits of pig slurry applications observed by Ceotto and Spallacci (2006) in Italy (8–43% yield increase). The authors attributed the yield increase to the lower costs of soil nitrate N reduction compared to N_2 symbiotic fixation.

The amounts of manure solids applied in our experiment ranged from 0.7 to 4.4 Mg ha^{-1} with no effect on alfalfa yield in the subsequent forage cut after pig slurry applications, whereas Lamb et al. (2005) found that applications of pig slurry at a rate above 3 Mg ha^{-1} of solids reduced alfalfa hay productivity.

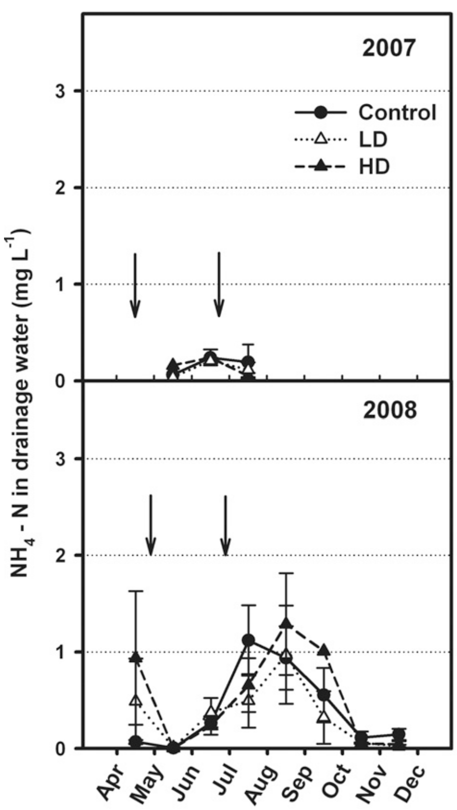

Fig. 5. Monthly average NH_4–N concentration (mg L^{-1}) in drainage water in the control, pig slurry low dose (LD) and pig slurry high dose (HD) treatments in 2007 and 2008. Vertical bars indicate standard error (*n* = 4). † HD data in September 2008 comes from one lysimeter due to missing data and therefore no error bars are shown.

Further information regarding yield effects of pig slurry applications to growing alfalfa stands is scarce. In a study with dairy slurry applications to alfalfa, Daliparthy et al. (1994) observed yield reductions with rates above 336 kg N ha^{-1}, lower than the rates applied in the HD treatment in the present experiment (354 and 403 kg N ha^{-1} in 2007 and 2008). The different conditions in the study conducted by Lamb et al. (2005), where no rain occurred during the week after the slurry application, and the rainfed conditions in the study by Daliparthy et al. (1994), could explain the lack of negative effects found in our experiment, where the crop was irrigated after each pig slurry application. Yield decreases in alfalfa associated to leaf burning or toxicity of slurry can be probably avoided by applying the slurry just before the regrowth of alfalfa and irrigating immediately after the application, which is feasible under sprinkler irrigated systems. In any case, the slight decrease in 2007 of alfalfa forage yield with the highest pig slurry dose compared to the low dose could be due to the slight increase of salinity found after the application of pig slurry under irrigated conditions (Diez et al., 2004).

Alfalfa N concentration and the derived crude protein content did not increase as a result of the pig slurry applications. However, plant δ^{15}N values showed the different origin of the plant N in the different treatments. Higher plant δ^{15}N values have been observed after applications of organic fertilizers such as pig manure (Choi et al., 2003) and liquid pig slurry (Lim et al., 2007) compared to inorganic N sources. Organic fertilizers have higher δ^{15}N values mostly due to a larger volatilization of ^{15}N compared to ^{14}N in NH_4, so the remaining N in the manure is enriched in ^{15}N (Choi et al., 2003). Thus, the increase in δ^{15}N values in the forage after each pig slurry application indicates that alfalfa was taking up N from the pig slurry and suggests that the proportion of N coming from N fixation or from soil N mineralization was reduced. Furthermore, the decreasing tendency of δ^{15}N values over time after each pig slurry application suggests that the proportion of plant N coming from fixation increased again as the pig slurry N was depleted from the soil. Therefore, in agreement with studies on biological N fixation (Lamb et al., 1995), a complete inhibition of N fixation did not seem to occur after N applications to alfalfa or it occurred for a reduced time period.

Total N content in the alfalfa forage averaged 607 kg N ha^{-1} yr^{-1}, much higher than the 278 to 347 kg N yr^{-1} obtained in previous studies with slurry and manure applications to alfalfa (Ceotto and Spallacci, 2006; Daliparthy et al., 1994; Toth et al., 2006). However, our results are similar to the 664 kg N ha^{-1} yr^{-1} reported by Lloveras et al. (2001) under similar agronomic and climatic conditions. Under our experimental conditions the ratio of N applied with the slurry/total N in the alfalfa forage was 0.26 and 0.53 in the LD and HD slurry treatments, respectively. Thus, the rest of N, 74% (for the LD treatment) and 47% (for the HD treatment), should have been obtained mostly from N fixation, considering the low soil inorganic N values found throughout the experiment. This is in agreement with the lower average plant $\delta^{15}N$ values found in the LD treatment (1.8‰) compared to the HD treatment (2.8‰).

The cumulative amounts of Cu and Zn applied with the pig slurry in the HD rate after 2 yr were 9 and 25.4 kg ha^{-1}, respectively, whereas uptake by alfalfa forage was only 10% of these amounts for both elements. In agreement with previous studies (Lloveras et al., 2004), this surplus of Cu and Zn can be the cause for the increased amounts of these elements in the alfalfa forage in the HD and LD treatments compared to the CT. The increased concentrations of Mg in the forage in the HD and LD treatments could be explained by a possible decrease in soil pH values with pig slurry applications reported in calcareous soils (Bernal et al., 1992) and the consequent higher availability of this element for the plants. In any case the heavy metals content of forage did not reach the thresholds established for animal toxicity proposed by the National Research Council (1980).

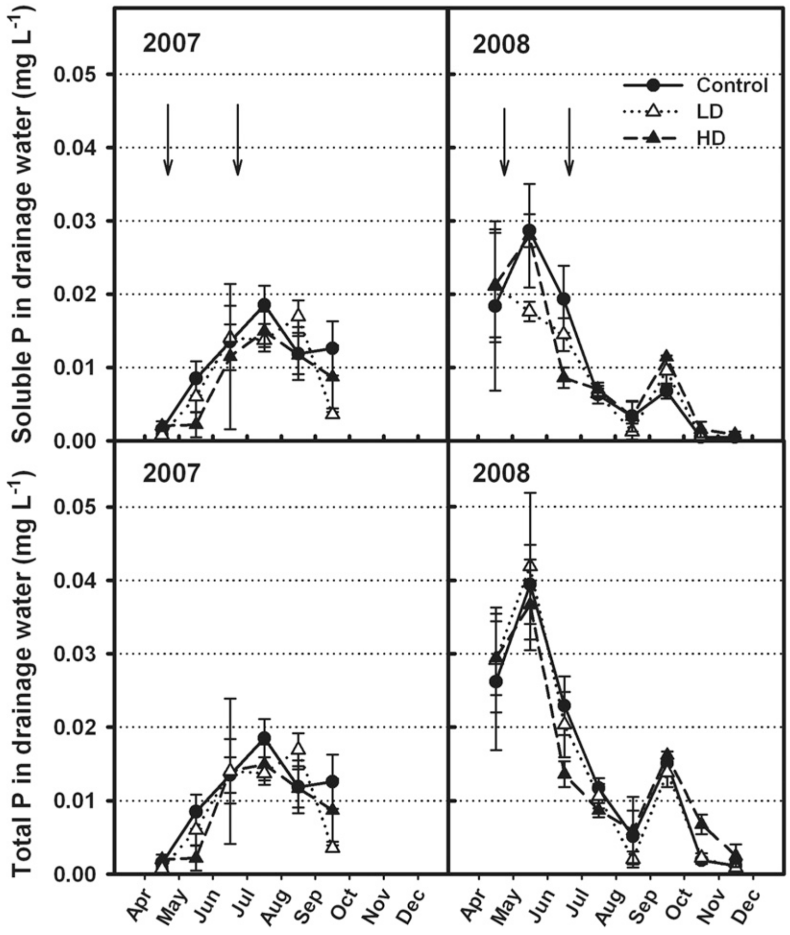

Fig. 6. Monthly average soluble and total P concentration in drainage water in the different treatments (control, pig slurry low dose [LD], and pig slurry high dose [HD]) during 2007 and 2008. The arrows indicate the dates of slurry application. Vertical bars indicate the standard error (*n* = 4).

Drainage Volume and Quality

Most drainage occurred during the growing period of alfalfa, linked to irrigation, and thus differs from other studies under rainfed conditions, where more than 75% of the drainage occurred during the nongrowing season (Toth et al., 2006; Basso and Ritchie, 2005). In these other studies most drainage occurred early in the season or after harvest. In the first year of the experiment (2006), the combined effect of the high drainage and the smaller N uptake by the alfalfa crop during its establishment could explain the higher nitrate concentration observed in the drainage water compared to the two following years. Significant N losses in the first year of alfalfa have been found also by others (Basso and Ritchie, 2005; Toth et al., 2006). Better irrigation management could help to reduce N leaching in drainage during the establishment period of alfalfa.

The very low nitrate concentration of drainage water in the two following years is consistent with other works in nonfertilized alfalfa (Randall et al., 1997; Toth and Fox, 1998) with average values of 3 mg N L^{-1} in drainage water and a total of 1 to 9 kg N ha^{-1} lost by leaching. However, information regarding N leaching losses is scarce and inconsistent, especially when alfalfa receives organic fertilizers. Basso and Ritchie (2005) reported increasing N leaching in alfalfa ranging from 10 to 115 kg N ha^{-1} under nonfertilizer and manured treatments, respectively. Other studies with dairy slurry (Daliparthy et al., 1994) and manure applications (Toth et al., 2006) also found higher nitrate concentration in drainage water (averaging 17.8 and 20 mg L^{-1}) than the obtained in our study with similar or lower rates of N applied. The lower N leaching observed in our study could be due to the absence of drainage during the nongrowing periods of the alfalfa, contrary to more humid climates where about 70% of N leaching occurs during this period (Basso and Ritchie, 2005; Toth et al., 2006). Second, N concentrations have been found to increase with increasing rates of N applied (Daliparthy et al., 1994; Basso and Ritchie, 2005; Toth et al., 2006), whereas in the present study, alfalfa receiving up to 403 kg N ha^{-1} yr^{-1} was able to maintain low soil inorganic N content avoiding nitrate leaching losses. This high efficiency could be explained by the fact that N applied with the slurry accounted only for 53% of the N in forage in the HD treatment and by the relatively high irrigation efficiency (>80%).

In the irrigated areas of the Ebro Valley, most drainage water from fields moves to natural or artificial drainage channels and to the rivers, so it pollutes mostly surface waters. The fact that P concentrations were in most drainage events below the threshold for eutrophication indicates a low eutrophication risk from this drainage water. The increasing total P concentrations and loads in drainage observed from 2007 to 2008 were associated to a higher amount of particulate P in drainage in 2008 (35%) compared to 2007 (19%). An hypothesis that could explain this is an increase in preferential water flows with time in a perennial crop

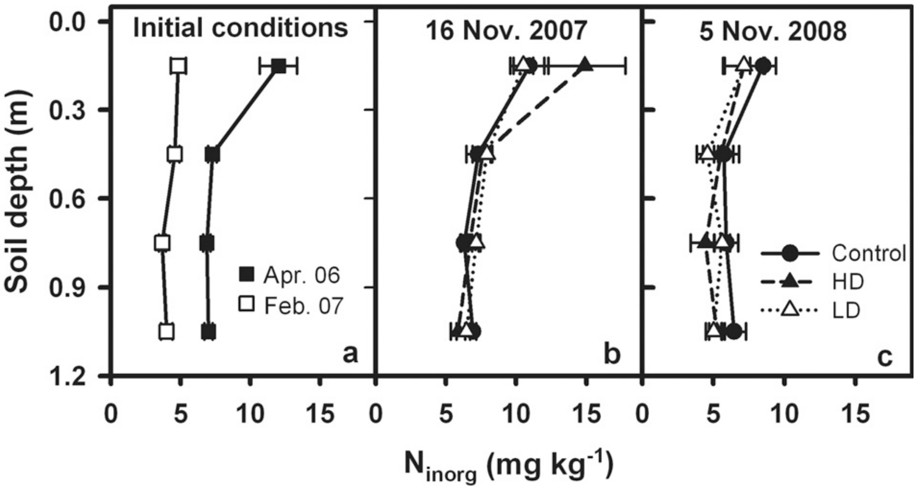

Fig. 7. Soil inorganic N content in the different treatments (control, pig slurry low dose [LD], and pig slurry high dose [HD]): (a) at the start of the experiment (2006), (b) at the end of the alfalfa growing season 2007, and (c) at the end of the alfalfa growing season 2008. Horizontal bars indicate the standard error (a) *n* = 12; (b) and (c) *n* = 4.

with a deep root system such as alfalfa. Total mass of P lost by drainage (0.035 kg ha^{-1} yr^{-1}) was lower than the 0.5 kg ha^{-1} yr^{-1} observed by Toth et al. (2006) in manured alfalfa, but similar to the 0.044 kg ha^{-1} yr^{-1} obtained by Brye et al. (2002) in maize.

Nitrogen, Phosphorus, and Heavy Metals Accumulation in the Soil

The low soil inorganic N content found in this study agrees with previous studies of fertilized alfalfa (Martin et al., 2006; Daliparthy et al., 1994; Schmitt et al., 1994). It is possible that soil inorganic N content increased after pig slurry applications in the upper soil layers, as observed by Ceotto and Spallacci (2006), but the high N uptake of alfalfa (608 kg N ha^{-1} yr^{-1}) allowed a reduction of this transient high N content in the soil avoiding soil inorganic N accumulation and subsequent leaching in drainage water. This high efficiency could be also explained by the relatively high water holding capacity of the soil and the deep rooting system of alfalfa, which makes this crop a relevant scavenger of subsoil N (Schmitt et al., 1994; Martin et al., 2006).

An average of 21% increase in soil P content was observed after 2 yr of pig slurry applications and inorganic fertilizer compared to the start of the experiment. This was related to an excess of P applied and supposes an increasing risk of P losses by runoff given that most P remains in the surface soil layer. Toth et al. (2006) reported a 20% soil P increase in the 0 to 0.05-m soil layer after 4 yr of N based liquid pig manure application, but little changes below this layer. In this experiment, a significant increase was observed in the 0- to 0.30-m depth plow layer, and consequently, much higher P concentrations should be expected in the first 5 cm soil layer. Thus, as previously proposed (Eghball and Power, 1999; Toth et al., 2006), P-based manure applications should be managed to avoid P buildup. When the soil has sufficient P available, Eghball and Power (1999) suggested that manure applications should be made taking into account a 100% P availability from the manure. For sustainable pig slurry applications in irrigated alfalfa in the conditions of our experiment, a liquid manure rate equivalent to 60 kg P ha^{-1} should be used. This is close to the low slurry rate used in this study. However, P content showed a tendency to increase in this treatment as well. Another option is to schedule the P requirements of all crops in the rotation instead of each crop separately, which can be economically more feasible and environmentally sound assuming that P losses by leaching and runoff are unimportant.

Surplus applications of Cu and Zn with pig slurry applications can accumulate into the soil (L'Herroux et al., 1997; Lloveras et al., 2004). Our results after 2 yr of pig slurry applications indicated no statistically significant increase in total soil Cu and Zn content although the 0- to 0.30-m soil layer showed a tendency to have higher Zn concentrations. Other studies under similar environmental conditions (Berenguer et al., 2008) suggest that at similar pig slurry application rate, it would take two to three centuries to build up the soil content of these elements to levels of phytotoxicity.

Table 4. Concentration of available P (Olsen), total Cu and Zn in the upper soil layers at the end of the experiment for the different treatments.

Treatment	P†	Cu	Zn
		mg kg^{-1}	
		0- to 0.3-m soil layer	
Control	38.3	59.0	94.5
Pig slurry low dose	40.5	55.0	110.3
Pig slurry high dose	40.8	57.3	109.3
		0.3- to 0.6-m soil layer	
Control	36.0	27.0	88.3
Pig slurry low dose	34.3	22.5	81.3
Pig slurry high dose	32.0	21.0	82.8

† For each soil layer/variable group, means having the same letter in common are not significantly different at the 5% level of significance as indicated by Fisher's Protected LSD test. The absence of letters within a group indicates that the treatment effect was nonsignificant in the ANOVA.

CONCLUSIONS

Application of pig slurry did not affect the forage yield and quality after 2 yr of alfalfa production. The absence of yield decreases in alfalfa (associated to leaf burning or toxicity from slurry) was probably due to the capability to irrigate immediately after pig slurry application. The high N uptake of alfalfa and its capability to adapt N fixation to the soil inorganic N content resulted in low nitrate concentrations of drainage water that were similar in the pig slurry and P–K fertilizer treatments. Thus, the N load in drainage water was lower than 2 kg N ha^{-1} yr^{-1}. The P losses in drainage water were very low (0.035 kg P ha^{-1} yr^{-1}) and were not affected by the pig slurry application. The soil P increased in the surface layer by 21% as a result of both pig slurry and P fertilizer applications. Application of pig slurry did not increase significantly the Zn and Cu content of the soil in the 0- to 30-cm layer.

Summer applications of pig slurry to growing alfalfa in the Ebro River Valley could increase the area and time for disposal of this residue without detrimental effects on alfalfa forage yield and quality and without environmental risks to soil and drainage water quality.

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Capítulo 3

Winter cover crops affect monoculture maize yield and nitrogen leaching under irrigated Mediterranean conditions

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Winter Cover Crops Affect Monoculture Maize Yield and Nitrogen Leaching under Irrigated Mediterranean Conditions

Montserrat Salmerón,* José Cavero, Dolores Quílez, and Ramón Isla

ABSTRACT

Under semiarid Mediterranean conditions irrigated maize (*Zea mays* L.) has been associated with nitrate pollution of surface water and groundwater. Cover crops grown during the intercrop period of maize could reduce N leaching. A 2-yr experiment was conducted in drainage lysimeters with three cover crops: barley (*Hordeum vulgare* L), winter rape (*Brassica rapa* L.), or common vetch (*Vicia sativa* L.). Bare soil was used as control treatment. Maize was fertilized with 300 kg ha^{-1} N in the control, and this amount was reduced after a cover crop according to the N content in the aboveground cover crop biomass. Barley and winter rape biomass had a higher N content than vetch (130–170 vs. 50 kg ha^{-1}). The vetch treatment did not reduce N leaching or affect maize yield. The barley and winter rape treatments reduced N leaching by 80% compared to the control (25 kg ha^{-1} yr^{-1}) mainly due to a reduction of NO_3–N concentration in drainage. Maize yield was reduced by 2.7 Mg ha^{-1} after barley and winter rape but still high (≈14 Mg ha^{-1}). This reduction was due to an N deficiency caused by lower soil N in spring after the cover crop and insufficient N mineralization and/or lack of synchronization with maize N uptake. To use nonlegume winter cover crops to reduce N leaching in monoculture maize it is necessary to consider that N mineralization may not be sufficient to fulfill maize N requirements and N fertilizer adjustment tools should be developed.

Maize grown in monoculture is very common in the irrigated areas of the Ebro River basin (Spain). Irrigation in these semiarid climatic conditions is the main water input for crops and enables high maize yields (15 Mg ha^{-1}) due to high solar radiation (Cavero et al., 2008). However, given its high N demand, maize has long been recognized as a major contributor to the diffuse pollution of return flows from irrigated areas in Spain (Díez et al., 1997; Cavero et al., 2003; Causape et al., 2004; Isidoro et al., 2006) and other irrigated areas of the world (Pratt, 1984; Klocke et al., 1999).

Nitrogen fertilization and irrigation management directly affect the amount of N leached in maize cropping systems. Surveys of growers in the irrigated areas of the Ebro Valley revealed that high N rates are applied to maize (318–453 kg ha^{-1} yr^{-1}) to avoid risks of yield losses (Cavero et al., 2003; Isidoro et al., 2006). On the other hand, reported N rates for maximum yields in the region range from 0 to 280 kg ha^{-1} (Isla et al., 2006; Berenguer et al., 2009), depending on available soil inorganic N at maize planting. Thus, excessive fertilizer N is often applied and large amounts of residual N are left in the soil at maize harvest (Villar-Mir et al., 2002). This residual N is prone to leach during the intercrop period (October–April) and at the start of the following maize growing season, when the crop N uptake is low and maize roots are not deep in the soil profile. Moreover, N leaching during the maize growing season can be relevant, as increases in nitrate concentration and loads in drainage water have been observed at the watershed scale after side-dress N application to this crop (Causapé et al., 2004; Isidoro et al., 2006).

In addition to the rates of N fertilizer applied, a proper irrigation management is a key factor to reduce nitrate loads in drainage water from irrigated areas (Martin et al., 1994; Schepers et al., 1995; Pang et al., 1997; Diez et al., 2000; Cavero et al., 2003; Causapé et al., 2006). The quality of irrigation application at field scale can be measured as the irrigation efficiency that is defined as the crop evapotranspiration divided by the total water applied as irrigation plus precipitation (Howell, 2003). Depending on the soil properties and irrigation management, irrigation efficiency at the field level can be low to moderate under surface irrigation (average 53–79%) but can reach high values in well-managed sprinkler irrigation systems (94%) (Causapé et al., 2006). Monitored watersheds in the Ebro River basin have reported annual losses ranging from 25 to 50 kg ha^{-1} N under sprinkler irrigation (Tedeschi et al., 2001; Cavero et al., 2003), and much higher N losses under surface irrigation, ranging from 35 to 195 kg ha^{-1} N (Causapé et al., 2006; Isidoro et al., 2006).

The growth of cover crops during the intercrop period can reduce nitrate concentrations and loads in drainage water (Dinnes et al., 2002). The positive effects of this practice to reduce N losses in maize have been reported mostly in humid areas of the United States (McCracken et al., 1994;

M. Salmerón, D. Quílez, and R. Isla, Soil and Irrigation Dep. (EEAD-CSIC Associated Unit), Agrifood Research and Technology Centre of Aragón (CITA), Aragon Government, Avda. Montañana 930, 50059 Zaragoza, Spain. J. Cavero, Dep. Suelo y Agua, Estación Experimental de Aula Dei (CSIC), Avda. Montañana 1005, 50059 Zaragoza, Spain. Received 21 Apr. 2010. *Corresponding author (msalmeronc@aragon.es).

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Abbreviations: ET, evapotranspiration; GNE, grain number per ear; KM, kernel mass; LAI, leaf area index.

Brandi-Dohrn et al., 1997; Isse et al., 1999; Rasse et al., 2000; Tonitto et al., 2006), Canada (Ball-Coelho et al., 2004), and France (Martinez and Guiraud, 1990). Legumes can be used as cover crops (Drinkwater et al., 1998) and are generally proposed to increase N availability for the following maize crop (Balkcom and Reeves, 2005), but greater N leaching losses than with cereals have been found (McCracken et al., 1994). In irrigated areas of the world winter cover crops have been recommended to avoid N leaching in rotations that include vegetable crops (Shennan, 1992; Poudel et al., 2001; Snapp et al., 2005), but there is little information on cover crop effects on monoculture maize. Cereal cover crops in nonirrigated maize often have a negative or no effect on grain yield when compared to a control treatment (Martinez and Guiraud, 1990; Kuo and Jellum, 2000; Holderbaum et al., 1990; Miguez and Bollero, 2005, 2006), whereas legume cover crops can increase maize yield (Holderbaum et al., 1990; Kuo and Jellum, 2000; Kuo et al., 1996; Decker et al., 1994; Utomo et al., 1990; Miguez and Bollero, 2005, 2006). Moreover, most of these studies were conducted under no-till maize which can have reduced N mineralization compared to tilled maize (Utomo et al., 1990; Astier et al., 2006).

In the Ebro River basin the use of cover crops is not a common practice, and studies of cover crops–maize rotations are not available. Results from studies in humid regions may not apply to semiarid regions such as the Ebro River basin which receives <200 mm of winter precipitation (Cavero et al., 2003; Causapé et al., 2006). A reasonable hypothesis is that cover crops grown after irrigated maize in these semiarid conditions could reduce residual mineral N in the soil, avoiding N losses during winter and during the early growth stages of maize the next season.

Snapp et al. (2005) reported the difficulties of adopting cover crops for economic reasons. To overcome this limitation in the absence of environmental public subsidies, the inclusion of a cover crop in the rotation should allow a reduction in the N fertilizer rate to the following maize crop. This reduction can be allowed when part of the N in the cover crop is mineralized and available to maize. Nitrogen mineralization from the cover crop and the effect on the subsequent maize crop can be variable and is affected by the C to N ratio of the plant residue (Ranells and Wagger, 1997; Holderbaum et al., 1990; Kuo et al., 1996). Cover crop N mineralization match with crop N uptake will depend also on weather and soil conditions, which makes it difficult to extrapolate the information obtained from different environmental conditions.

To evaluate the feasibility of using cover crops to reduce nitrate losses by leaching under irrigation in semiarid conditions, three different winter cover crops were studied in a maize monoculture system during 2 yr. The amount of N fertilizer applied to the next maize crop was reduced according to the N content of the cover crop. These strategies were studied with the aim of quantifying their effects (i) on the subsequent maize crop yield and (ii) on the volume, nitrate concentration, and nitrate mass in drainage.

MATERIALS AND METHODS

Site and Experimental Design

The experiment was performed from 2006 to 2008 at the CITA experimental fields, located in the Ebro Valley (41°44′ N, 0°49′ W) in Zaragoza, Spain. Maize and winter cover crops were grown in 12 drainage lysimeters (5.2 m^2 × 1.5 m depth). The lysimeters had been filled up 10 yr before the experiment started with a silt loam soil (233 g kg^{-1} sand, 510 g kg^{-1} silt, and 260 g kg^{-1} clay) with a 0.37 m^3 m^{-3} water content at field capacity (−0.033 MPa) and 0.17 m^3 m^{-3} water content at wilting point (−1.5 MPa). This is a calcareous soil with a $CaCO_3$ equivalent of 326 g kg^{-1} and a pH of 8.2 (water). Organic matter content at the start of the experiment (spring 2006) was 22 g kg^{-1} at all lysimeter depths. Crops previous to the start of the experiment were maize in monoculture (9 yr) and 1 yr (2005) of unfertilized sunflower (*Helianthus annuus* L.).

Table 1. Nitrogen applied to maize as green manure (cover crop aboveground biomass) and as synthetic fertilizer in the different treatments in 2007 and 2008.

Treatment	Cover crop biomass†	Preplant fertilizer	Sidedress fertilizer	Total
	N			
	kg ha^{-1}			
		2007		
Control	–	100	200	300
Barley	156	50	104	310
Winter rape	126	50	102	278
Common retch	43	50	216	309
		2008		
Control	–	100	200	300
Barley	127	50	109	286
Winter rape	119	50	116	285

† Nitrogen in the cover crop biomass excludes the material removed for N and C analysis.

Three cover crop treatments were tested during the intercrop period of maize: winter barley, common vetch, and winter rape. Bare soil was the control treatment. Treatments were randomly assigned to lysimeters configuring a completely randomized experimental design with three replicates. In the first cropping season of maize (2006) a dose of 300 kg ha^{-1} N was applied to maize simulating the standard N rate used in the irrigated areas of the Ebro Valley (Spain). In the following years (2007 and 2008), maize in the control treatment was fertilized with 300 kg ha^{-1} N, and treatments with winter cover crops received an N fertilizer rate that was reduced from the 300 kg ha^{-1} N by the N contained in the aboveground biomass of the cover crop incorporated to the soil (Table 1).

Maize 'Pioneer PR34N43' was planted on 28 Apr. 2006, 24 Apr. 2007, and 15 Apr. 2008 to obtain a final plant density of 84,600 plants ha^{-1}. The area between the lysimeters was also grown with maize to avoid border effects. Maize grain was harvested each year in October and plant stover was left in the field and incorporated into the soil with a power tiller. Cover crops were planted as soon as possible after maize harvest and seedbed preparation, on 30 Oct. 2006 and 23 Oct. 2007 at seeding rates of 180, 12, and 110 kg ha^{-1} for barley, winter rape, and common vetch, respectively. The cover crops were mechanically incorporated into the soil on 19 Mar. 2007 and 12 Mar. 2008 with a power tiller. In the control treatment the same soil tillage practices were implemented.

Maize N fertilization was split with 50 kg ha^{-1} N (100 kg ha^{-1} N in the control) at preplant (urea, 46% N) and the rest in two equal side-dresses at the V6-V7 and V12 growth stages (ammonium nitrate, 33.5%) (Table 1). Maize was irrigated twice a week using a dense drip irrigation system that simulated flood irrigation (averaged flow of 17.3 L m^{-2} h^{-1}). The weekly irrigation requirements were calculated from the daily reference evapotranspiration

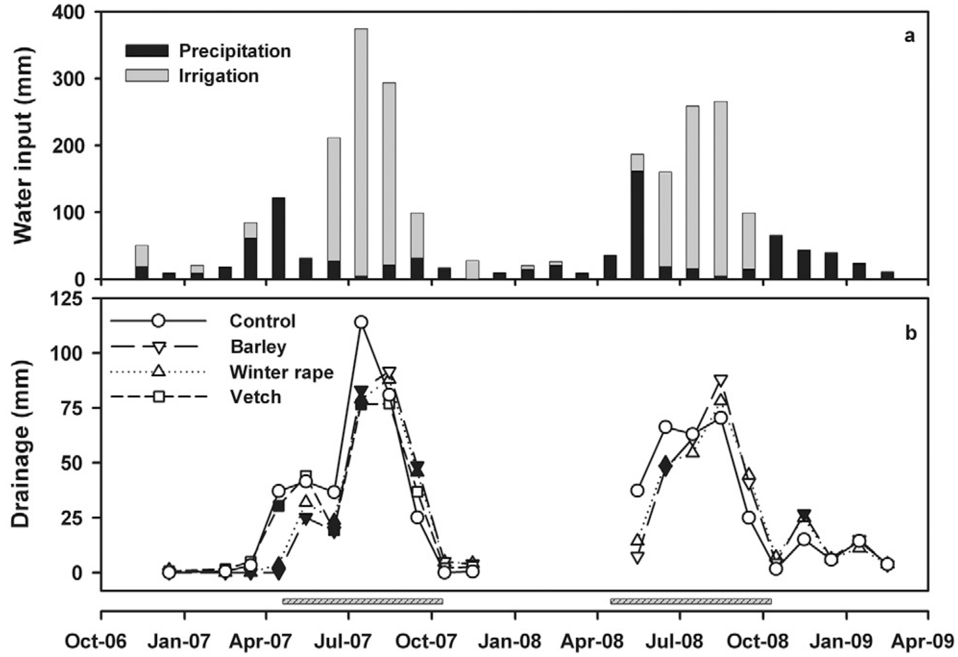

Fig. 1. Monhly values of (a) total water input (precipitation + irrigation) and (b) water drainage from the lysimeters in the different treatments during the experiment. Horizontal gray bars at the base of the graph indicate the maize growing season. The closed (black) symbols in the drainage figure (b) indicate significant differences from the control treatment within each date at *P* < 0.05 after ANOVA.

(estimated with the Penman–Monteith equation) and the crop coefficients, according to the FAO procedures (Allen et al., 1998) and considering a leaching fraction of 25%. The volume of water applied in each irrigation event was measured with a flowmeter (MFSM 25 mm, Hidroconta, Murcia, Spain). Total water applied as irrigation plus precipitation during the maize growing season was 1010 and 962 mm for 2007 and 2008, respectively, and monthly values over the 2 yr are shown in Fig. 1a. Weed and pest control were made according the standard practices of the area to ensure an adequate growth of the maize crop.

Cover Crops and Maize Growth Analysis

Cover crops were sampled before being incorporated into the soil by harvesting the aboveground biomass in two 0.25 m^2 samples per lysimeter. Leaf area was measured with a leaf area meter (LI-3000, LI-COR, Lincoln, NE) to calculate the leaf area index (LAI). The sample was then oven dried at 65°C, weighed, finely ground and analyzed for total N and C by combustion (TruSpec CN, LECO, St. Joseph, MI). The amount of cover crop aboveground biomass sampled was stored for analysis and not added as green manure (Table 1).

Leaf greenness of maize was measured during the growing season with a chlorophyll meter (SPAD-502, Minolta Camera Co., Ltd., Osaka, Japan). Measurements were done on the youngest fully developed leaf until the silks emerged and on the ear leaf later on. The average from 30 readings in different plants within each lysimeter was calculated.

Maize was hand harvested on 5 Oct. 2006, 9 Oct. 2007, and 9 Oct. 2008. All ears in each lysimeter were collected to determine grain yield, grain number per ear (GNE), kernel mass (KM), and grain moisture content. All the plants contained in each lysimeter were weighed and a subsample of two plants was taken. Two cobs were added to the plant subsample after separating the grains. Grain and the two plants (plus cobs) were oven dried at 65°C, weighed, ground, and analyzed for total N and C. Grain yield is reported on the basis of 140 g kg^{-1} moisture content.

To evaluate the end-of-season nitrate test, maize stalks were collected at harvest from 15 plants from each lysimeter following the procedure described by Binford et al. (1992). In all cases the sheaths were removed from the stalks, then the stalks were oven dried at 65°C until constant weight, and ground. A subsample of 2 g was extracted with 50 mL of KCl 2N, shaken for 30 min, filtered through a cellulose filter (Whatman no. 1) and analyzed with a continuous flow analyzer by spectrophotometry UV-Vis (Iris Advantage Ers Duo, Thermo Fisher Scientific, Franklin, MA).

Water Drainage and Soil Analysis

Drainage from each lysimeter was collected in 50 L tanks set in an underground room. Drainage volume was measured on a weekly basis, and a sample of 100 mL was collected to analyze the NO_3^-–N concentration colorimetrically with a continuous flow analyzer (AA3, Bran+Luebbe, Norderstedt, Germany).

Soil was first sampled on 26 Apr. 2006 and then twice each year, after maize harvest and before cover crop incorporation. Two soil cores from each lysimeter were taken with a 5 cm diam. hand auger (Eijkelkamp Agrisearch Equipment BV, Giesbeek, The Netherlands) and combined per depth in 0.3-m increments to 1.2-m depth. Soil samples were dried at 105°C to constant weight for gravimetric water content determination. Soil extracts were prepared using 10 g of fresh-sieved (2 mm) soil and 30 mL of KCl 2 M for determination of NO_3^-–N concentrations colorimetrically.

Water and Nitrogen Balances

The evapotranspiration in each lysimeter was calculated based on a water balance between two soil sampling dates. Inputs considered were initial soil water content, irrigation, and precipitation. The outputs were final soil water content, drainage, and evapotranspiration.

The mineralization during the maize crop cycle was estimated using an N budget (0–1.20 m). Inputs considered were soil mineral N before cover crop incorporation ($N_{inorg\ I}$), N in irrigation and rain (N_{irr}) and N applied as fertilizer (N_F). Outputs included were soil mineral N at maize harvest ($N_{inorg\ F}$), maize N uptake (N_{uptake}), and nitrate leaching (N_{leach}). Soil mineral N is the sum of NO_3^-–N and NH_4^+–N. The unbalance term (ΔN) would include soil and maize stover net mineralization, N losses by volatilization and denitrification, and N mineralization of the cover crop biomass.

$$\Delta N = N_{inorg\,F} + N_{uptake} + N_{leach} - N_{inorg\,I} - N_F - N_{irr} \quad [1]$$

Statistical Analysis

Statistical analyses were performed using ANOVA and general linear model (GLM) procedure of the SAS 9.1 software (SAS Institute, 2004). Multiple comparisons among treatments were performed using Fisher's Protected LSD test at $P = 0.05$. Values of soil N_{inorg} and maize stalk NO_3^-–N were transformed before analyses by the function $y = \log(x)$ to obtain homogeneity of variances.

RESULTS

Cover Crop Biomass Production and Nitrogen Uptake

The weather conditions in the experiment enabled high barley and winter rape aboveground biomass production during the two intercrop periods studied, as indicated also by the LAI values reached in spring (Table 2). In the second intercrop period (2007–2008), barley produced more aboveground biomass than winter rape. Common vetch was damaged by winter frost during the 2 yr. The first year vetch growth was low and aboveground biomass and LAI was lower than barley and rape cover crops (Table 2). In the second year, vetch was completely killed and therefore data for this treatment are not presented. Nonlegume cover crops were at the start of blooming when incorporated into the soil in March the second year of the experiment.

Table 2. Cover crop aboveground biomass, N uptake and concentration, C/N ratio, and leaf area index (LAI) before incorporating the cover crops into the soil in spring 2007 and 2008.

Cover crop	Biomass	N Uptake	N Concentration	C/N	LAI
	Mg ha^{-1}	kg ha^{-1}	%		m^2 m^{-2}
			2006–2007		
Barley	6.95 a†	173 a	2.52 b	17.3 a	6.53 a
Winter rape	5.46 a	139 a	2.52 b	16.3 a	5.63 a
Common vetch	1.00 b	48 b	3.92 a	9.9 a	1.22 b
			2007–2008		
Barley	7.01 a	141 a	1.99 a	21.4 a	5.18 a
Winter rape	5.26 b	131 a	2.46 a	15.3 a	5.40 a

† For each variable and year, values followed by the same letter are not significantly different after ANOVA according to a Fisher Protected LSD test at the 0.05 probability level.

The N uptake of barley and winter rape averaged 157 and 135 kg ha^{-1}, respectively, over the 2 yr. No significant differences were found in N uptake, N concentration, and C /N ratio between barley and winter rape (Table 2). On the other hand, the N concentration of the vetch residue was higher than that of the nonlegume cover crops, and its C/N ratio was lower but not significantly (Table 2). The N uptake of common vetch (48 kg ha^{-1}) was lower than that of the nonlegume cover crops due to the low biomass produced (Table 2).

Maize Grain Yield, Yield Components, and Nitrogen Uptake

Maize grain yields were in the high range for the region (Cavero et al., 2003; Isla et al., 2006; Berenguer et al., 2009) (Table 3). In both years the barley and winter rape treatments reduced maize yield compared to the control (Table 3), with an average decrease of 2.7 Mg ha^{-1}. The common vetch treatment produced a maize yield similar to the control. In 2007 total aboveground biomass of maize was reduced in the winter rape treatment compared to the control, and the barley treatment also had a lower maize biomass than the control, although not significantly (Table 3). The vetch treatment produced the largest aboveground biomass of maize, which did not differ from the control. In 2008, the total aboveground biomass of maize in the

Table 3. Maize grain yield (at 140 g kg^{-1} moisture content), total aboveground biomass, harvest index (HI), grain number per ear (GNE), kernel mass (KM), stalk NO_3–N, N concentration in grain and plant, and N uptake in grain and plant for each treatment and year.

Treatment	Grain	Total biomass	HI	GNE	KM	Stalk NO_3^-–N	N concentration Grain	N concentration Plant	N uptake Grain	N uptake Plant
	Mg ha^{-1}	Mg ha^{-1}		no.	g	mg kg^{-1}	%	%	kg ha^{-1}	kg ha^{-1}
						2007				
Control	16.9	29.3 ab	0.50	631	0.291	323	1.45 a	0.76	211 a	324 a
Barley	13.9	24.9 bc	0.48	529	0.275	17	1.17 b	0.66	141 b	228 b
Winter rape	14.2	22.7 c	0.54	569	0.258	29	1.15 b	0.64	142 b	210 b
Common vetch	17.8	30.8 a	0.50	622	0.298	334	1.42 a	0.82	217 a	345 a
P†	0.054	0.04	ns‡	ns	ns	0.07	0.02	ns	0.01	0.01
						2008				
Control	16.4 a§	27.6	0.51	581	0.280	905 a	1.50	0.83 a	212	324 a
Barley	13.8 b	25.0	0.48	563	0.250	76 b	1.40	0.69 b	168	258 b
Winter rape	13.8 b	25.2	0.47	537	0.259	46 b	1.38	0.63 b	162	247 b
P	0.01	ns	0.08	ns	ns	0.01	NS	0.02	0.08	0.03

† Probability level of the treatment effect after ANOVA.
‡ ns: (P > 0.10).
§ For each variable and year, values followed by the same letter are not significantly different after ANOVA according to a Fisher Protected LSD test at the 0.05 probability level.

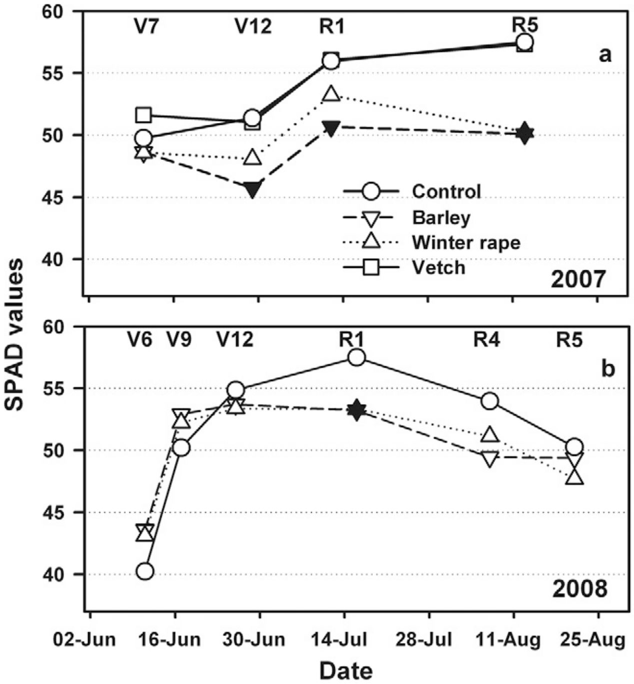

Fig. 2. Average SPAD values in the different treatments during the maize growing season in (a) 2007 and (b) 2008. (V7: 7-leaf stage; V9: 9-leaf stage; V12: 12-leaf stage; R1: silking; R4: dough; R5: dent). The closed (black) symbols indicate significant differences from the control treatment within each date at *P* < 0.05.

barley and winter rape treatments was lower than the control but differences were not significant. The harvest index (HI) was not significantly affected by the cover crop treatments (Table 3).

Barley and winter rape treatments had fewer grains per ear (GNE) and lighter kernels (KM) than the control, although differences were not statistically significant (Table 3). Regression analysis showed that grain yield increased as the GNE increased in 2007 ($P < 0.001$, $R^2 = 0.74$), but not in 2008 ($P = 0.08$, $R^2 = 0.29$), whereas grain yield increased with increases in KM in both years ($P < 0.001$ and $R^2 = 0.70$ in 2007; $P = 0.003$ and $R^2 = 0.59$ in 2008).

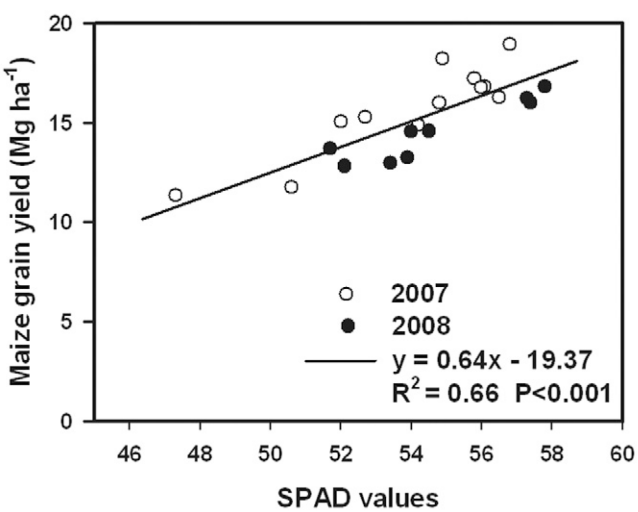

Fig. 3. Relationship between maize grain yield and SPAD values of maize leaves at silking (R1). Data pooled from all treatments and years.

Nitrogen uptake in the grain and in the aboveground biomass of maize was similar both years in the control treatment (Table 3). The barley and winter rape treatments reduced grain and total aboveground N uptake of maize by 33 and 22% in 2007 and 2008, respectively (although not significantly in grain uptake in 2008). In 2007 the vetch treatment did not affect grain and aboveground biomass N uptake of maize compared to the control (Table 3).

In 2007 the leaves of maize grown after barley had lower SPAD values than the control from V12 until R5 (Fig. 2). Similar results were observed for winter rape but differences were only significant at R5. The leaves of maize grown after vetch showed similar SPAD values to the control (Fig. 2). In 2008 the SPAD values of maize leaves were similar for all treatments in each date except at maize silking, when leaves of maize grown after barley and winter rape had lower SPAD values compared to the control (Fig. 2). Analysis of regression with data pooled from both years showed that grain yield was well related to SPAD values of maize leaves at the R1 stage (Fig. 3). The maize stalk nitrate test revealed lower nitrate concentrations in the barley and winter rape treatments ($P = 0.07$ in 2007) compared to the control treatment (Table 3). The vetch treatment had similar stalk nitrate concentration to the control.

Nitrogen Leached in Drainage Water

Drainage occurred mainly during the maize growing season, averaging 276 mm yr^{-1} across all treatments and years (Table 4, Fig. 1). Drainage during the maize growing season was 27% of total water applied (precipitation+irrigation), which is close to the leaching fraction used for irrigation scheduling (25%). There was one exception in 2007, where drainage in the control treatment was slightly higher (33% of water inputs). On the other hand, precipitation plus irrigation during the intercrop maize period was 40 mm lower than calculated evapotranspiration, and almost no drainage was observed during this time (Table 4). Cumulative evapotranspiration and drainage during the maize growing season were not different among treatments (Table 4). However, when looking at monthly values of drainage over time (Fig. 1b), a significant effect of the cover crop treatments was observed that can be decomposed into two periods. First, drainage from April–May to July was reduced in the cover crop treatments compared to the control. And second, from August to September–November, drainage was slightly higher in the cover crop treatments compared to the control (only significantly in September 2007 and November 2008).

The NO_3^-–N concentration in drainage water during the maize intercrop period was very low and was not affected by the treatments (Table 4). However, during the maize growing season, the NO_3^-–N concentration in drainage water was much higher in the control than in the barley and winter rape treatments (Table 4), with significant increases after the side-dress N fertilizer applications (Fig. 4a). Values of NO_3^-–N concentrations in drainage water in the control and vetch treatments were above the threshold of 10 mg L^{-1} NO_3^-–N in 19 and 45% of samples during the maize growing season in 2007 and 2008, respectively, while NO_3^-–N concentrations in the barley and winter rape treatments never exceeded that limit (data not shown). The barley and winter rape treatments reduced the NO_3^-–N concentration in drainage by 75% (2007) and 82% (2008) compared to the control (Fig. 4a), with flow weighed average concentrations below 2 mg NO_3^-–N L^{-1} (Table 4). The vetch treatment did not decrease the NO_3^-–N concentration of drainage water compared to the control (Table 4). On the contrary, it increased the NO_3^-–N concentration in drainage water in some months during the 2007 maize growing season (Fig. 4a).

During the intercrop period the low NO_3^-–N concentration in drainage water and the low water drainage resulted in negligible N leaching (Table 4). Averaged over the 2 yr, the mass of N lost in drainage during maize growing season was 25 kg ha^{-1} yr^{-1} in the control treatment. This amount was reduced by 80% in the barley and winter rape treatments, mainly due to the lower NO_3^-–N concentration in drainage water. The reduction started in April–May and continued to the end of July (Fig. 4b). The vetch treatment did not affect the mass of N lost in drainage during maize growing season 2007 when compared to the control (Table 4). However, N load in drainage water in May ($P = 0.07$) and in August 2007 was higher in the vetch treatment than in the control (Fig. 4b).

Soil Mineral Nitrogen and Nitrogen Balance

Soil inorganic N (N_{inorg}) before maize planting was variable among years at depths from 0 to 1.2 m in the control treatment (Fig. 5a, b, and c), with inorganic N concentrations in the soil profile equivalent to 206 kg ha^{-1} in 2006, 309 kg ha^{-1} in 2007, and 74 kg ha^{-1} in 2008. When cover crops were grown after maize, soil N_{inorg} the following spring was significantly lower in all the profile compared to the control treatment (Fig. 5b and c). The reduction of soil N_{inorg} was greater when barley and winter rape were grown, but less when common vetch was grown in 2007. At maize harvest, soil N_{inorg} in the control treatment was low in general and similar in all the soil profile (Fig. 5d, e, and f). Soil N_{inorg} in the upper soil layer (0–0.3 m) was on average

Table 4. Precipitation plus irrigation, evapotranspiration (ET), drainage volume, flow weighed NO_3^-–N concentration, and mass of NO_3–N leached from the lysimeters in the different cover crop treatments during the maize growing and non-growing seasons (NGS).

Period and treatment	Precip. + Irrig.	ET	Drainage Volume	Drainage NO_3^-–N	Drainage NO_3^-–N mass
	mm	mm	mm	mg L^{-1}	kg ha^{-1}
NGS 2006–2007	129				
Control		163 a†	3 b	2.97 a	0.10 ab
Barley		199 a	0 b	‡	0.00 b
Winter rape		186 a	1 b	0.36 a	0.01 b
Common vetch		153 a	7 a	2.76 a	0.20 a
Maize 2007	1010				
Control		643 a	336 a	6.92 a	23.2 a
Barley		654 a	272 a	1.81 b	4.9 b
Winter rape		683 a	277 a	1.67 b	4.6 b
Common vetch		692 a	286 a	9.68 a	27.7 a
NGS 2007–2008	103				
Control		130 a	0 b	0.27 a	0.01 a
Barley		158 a	4 a	0.08 a	0.01 a
Winter rape		132 a	4 a	0.02 a	0.01 a
Maize 2008	962				
Control		691 a	263 a	10.23 a	26.9 a
Barley		692 a	250 a	1.93 b	4.8 b
Winter rape		717 a	247 a	1.71 b	4.2 b

† For each period and variable, values followed by the same letter are not significantly different after ANOVA according to a Fisher Protected LSD test at the 0.05 probability level.

‡ No drainage.

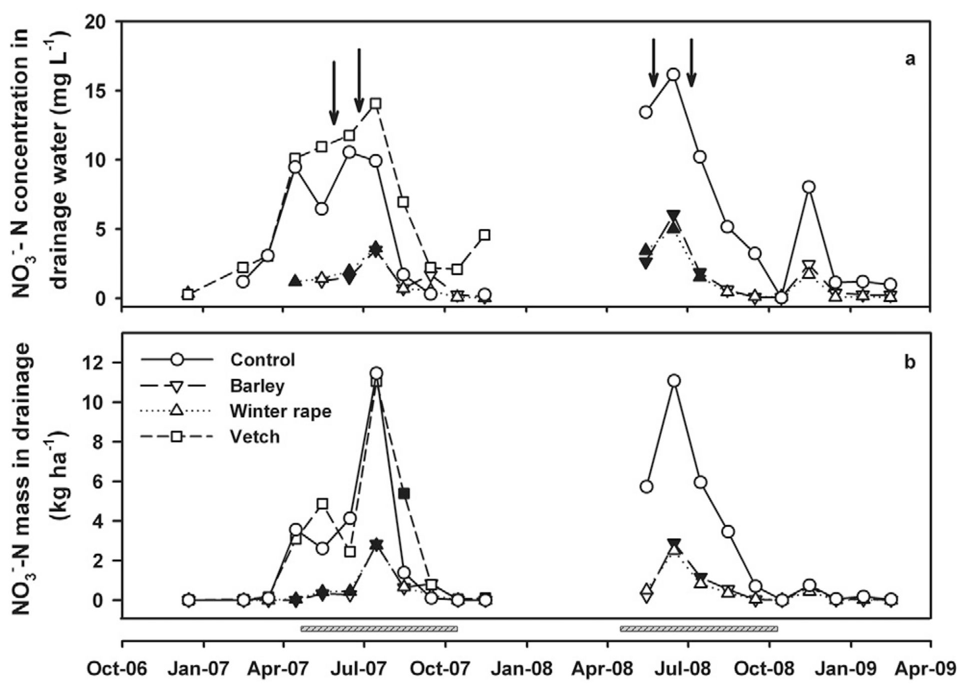

Fig. 4. Monthly average values of (a) NO_3^-–N concentration and (b) NO_3^-–N mass in the drainage water from the lysimeters in the different cover crops treatments. The horizontal gray bars at the base of the graph indicate maize growing seasons. The arrows indicate the dates of N fertilizer side-dress applications. The closed (black) symbols indicate significant differences from the control treatment within each date at $P < 0.05$ after ANOVA.

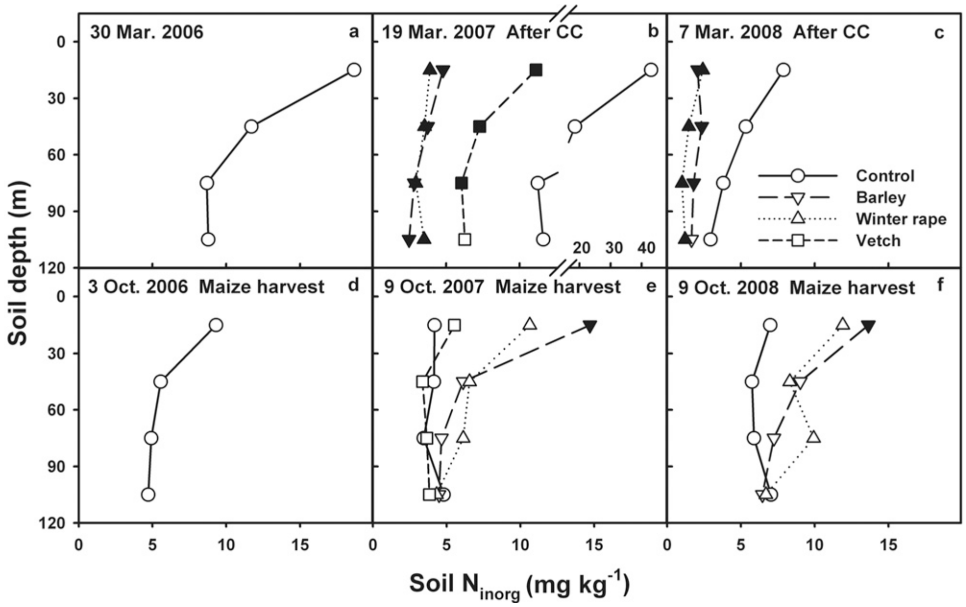

Fig. 5. Mineral N (N_{inorg}) in the soil profile in the different cover crops treatments (a) before maize sowing in 2006, (b) after growing cover crops (CC) and before incorporation of cover crops into the soil in spring 2007, and (c) 2008, and (d,e, and f) each year at maize harvest. Closed (Black) symbols indicate significant differences from the control treatment within each date at *P* < 0.05.

33 kg ha^{-1} higher in the barley and winter rape treatments compared to the control in both years (Fig. 5e and f) ($P < 0.1$ in the winter rape treatment), but no differences among treatments were found below 0.3 m soil depth at maize harvest.

In the control treatment the unbalance term of the N budget (ΔN) during the maize growing season 2007 was negative (Table 5), indicating either significant N losses to the atmosphere or N immobilization, which could be related at least in part to high C/N ratio of the previous year maize residue incorporated into the soil. In the following year (2008), the unbalance term of the N budget (ΔN) in the control treatment was positive indicating that net N mineralization was important this year and overcame any atmospheric N losses. The ΔN term was positive and significantly higher in the barley, winter rape, and vetch treatments than in the control treatment, indicating net N mineralization in the cover crops treatments. The estimated mineralized N in 2007 in the nonlegume cover crops was slightly lower than the N in the aboveground biomass of cover crops. However, in 2008 the estimated N mineralized in these treatments was much higher than the N in the aboveground biomass of cover crops.

DISCUSSION

Cover Crops Effect on Maize Yield

The cover crop effect on the subsequent cash crop N availability has been defined as a combination of the cover crop effect on soil N_{inorg} in spring and the N mineralization after the incorporation of the cover crop biomass (Thorup-Kristensen et al., 2003). In our experiment N availability for maize was also affected by the N fertilizer rate applied. All treatments were supplied with a similar total amount of N (close to 300 kg ha^{-1}) as fertilizer plus N in the cover crop aboveground biomass, assuming that most of the N in the cover crop residue will mineralize throughout the season due to its relative low C/N ratio. According to studies in the Ebro River basin this amount of N should be enough to achieve maximum maize yields, as optimum N fertilizer rates ranged from 0 to 280 (Isla et al., 2006). However, the lower N content in the maize grain and aboveground biomass, and the lower SPAD values in maize leaves at silking found in the barley and winter rape treatments suggest that the yield reduction in these treatments was due to an N deficiency. Moreover, the low stalk NO_3–N found in maize after the winter growth of these nonlegume cover crops

Table 5. Nitrogen content and C/N ratio of previous year maize stover at harvest and cover crop biomass incorporated in spring. Nitrogen unbalance term (ΔN) and final soil inorganic N at maize harvest.

Treatment	Previous year maize stover		Cover crop biomass		ΔN‡	Final soil N_{inorg}
	N content	C/N ratio	N content	C/ N ratio		
	kg ha^{-1}		kg ha^{-1}		kg ha^{-1}	
			Maize growing season 2007			
Control	42	61		–	–212 c†	72
Barley	33	65	156	17.3	143 a	130
Winter rape	42	50	126	16.3	102 ab	120
Vetch	43	55	43	9.9	–4 b	71
			Maize growing season 2008			
Control	108	55		–	85 b	127
Barley	84	64	127	21.4	227 a	158
Winter rape	65	68	119	15.3	219 a	162

† For each period and variable, values followed by the same letter are not significantly different after ANOVA according to a Fisher Protected LSD test at the 0.05 probability level.
‡ ΔN = Nuptake + Nleached – N fertilizers + ΔN mineral soil.

suggests that N deficiency occurred in maize, as NO_3–N contents were much lower than the threshold of 250 mg kg^{-1} for N deficiency proposed by Binford et al. (1992).

In the control treatment the high C/N ratio of the maize residue incorporated into the soil resulted in high N immobilization during the maize growing season in one of the years. However, the high N input as fertilizer (300 kg ha^{-1} N) and the very high soil N_{inorg} at maize planting in this treatment avoided maize yield reductions. Nitrogen mineralization during the maize growing season in the cover crop treatments (from maize residue, soil organic matter, and cover crop biomass) was higher than in the control treatment because cover crops are a fresh organic residue with a relatively low C/N ratio (9.9–21.4). The reported C/N ratio thresholds for net N immobilization are higher than 25 (Allison, 1966; Kuo and Jellum, 2000). The high and positive value for ΔN term of the N budget in the barley and winter rape treatments indicates that a great part of the N in the cover crop biomass was mineralized during the maize growing season in both years.

Nitrogen deficiency can occur if N release from organic sources is not synchronized with the N demand by the crop (Magdoff et al., 1990; Cavero et al., 1997). This could happen in the nonlegume cover crop treatments because at maize harvest, 53 and 33 kg ha^{-1} more soil N_{inorg} (mainly in the top layer) was found in these treatments compared to the control (Table 5). A timed N release is especially relevant in crops with determinate growth habit such as maize, especially when they have a high N demand in a short period of time.

Maize N deficiency in the barley and winter rape treatments could be also partially attributed to a lower initial soil N_{inorg} at preplanting, as the primary effect of the cover crops in the subsequent maize crop has been attributed to their influence on inorganic soil N content during spring (Kuo and Jellum, 2000). However, in our experiment this effect seemed to be minimal, as N deficiency during the maize vegetative phase revealed by the SPAD measurements were minimal in 2007 and absent in 2008.

A cover crop may increase the yield of the subsequent cash crop by providing more N to that crop. This is more likely to occur in humid climates or on sandy soils with significant N leaching losses (Andraski and Bundy, 2005; Bundy and Andraski, 2005; Clark et al., 1997; Vyn et al., 1999). In these conditions cover crops can take up soil N and avoid significant N losses during winter. Thus, in spring this N will be available after mineralization and the cash crop will have more N available than when planted on soil that was bare during winter, where a significant part of the soil N_{inorg} has been leached or moved to deeper soil layers (Thorup-Kristensen et al., 2003). However, under the conditions of low N leaching during winter found in our work, the barley and winter rape cover crops did not increase the N availability for maize.

To match maize N uptake and avoid yield reductions, cover crop management and N fertilization should both be optimized. In our irrigated conditions, N fertilizer rates of 150 kg ha^{-1} after barley and winter rape caused reductions in maize yields, but yields were still high (on average 14 Mg ha^{-1}). Given that the lower SPAD measurements in maize leaves revealed maize N deficiency in barley and winter rape treatments, this tool could be useful to detect N deficiency and to correct N fertilizer rates in maize after a cover crop, as previously reported in a cover crop-maize study (Miguez and Bollero, 2006) and in continuous maize (Scharf et al., 2006; Zhang et al., 2007). Late applications of N fertilizer by fertigation is a feasible practice under the sprinkler systems used in many irrigated areas of Spain (Cavero et al., 2003). In the legume cover crops, SPAD measurements near the tasseling stage could indicate N sufficiency and avoid N overfertilization.

Decreased availability of water for maize due to the inclusion of a cover crop has been reported in rainfed maize (Corak et al., 1991) and could be relevant under Mediterranean conditions, where water is a limiting factor and winter precipitation can be low. However, in the irrigated conditions of this experiment evapotranspiration was not affected by treatments during the winter period and during the maize growing season and only a small reduction in drainage (30–40 mm) at the start of irrigation was found in the cover crop treatments. This reduction of drainage is a positive effect for the reduction of nitrate leaching.

Cover Crops Effect on Nitrate Leaching

Nitrate leaching in the control treatment, which represents the standard management of maize in the Ebro River basin, was relatively low compared to results and estimations from previous studies in the area (Isla et al., 2006; Berenguer et al., 2009), and other studies in semiarid conditions (Pratt, 1984; Moreno et al., 1996; Klocke et al., 1999; Díez et al., 2000). This could be due to the high water holding capacity of the soil used in the lysimeters (200 mm), and the relatively high irrigation efficiency observed in the experiment compared to field conditions. Lower irrigation efficiencies are often observed under field conditions in watershed studies due to low irrigation uniformity and lower water holding capacity of the soils, so N losses higher than 50 kg ha^{-1} yr^{-1} N are frequent in irrigated watersheds in the Ebro River basin (Causape et al., 2004; Isidoro et al., 2006).

Due to low precipitation during the two intercrop periods of maize, N leaching could be linked to the irrigation applied during the maize growing season. Previous studies in the Ebro River basin have shown that most drainage occurs during the maize crop season rather than during the intercropping period (Yagüe and Quílez, 2010, Díez et al., 2000; Saad, 1999). Also, studies at the watershed level in the Ebro River basin have reported that most N leaching occurs during the irrigation season, although some N is leached during the nonirrigated periods (Cavero et al., 2003; Causapé et al., 2006). Studies in irrigated maize in semiarid areas in the United States (Klocke et al., 1999; Pratt, 1984) and other irrigated semiarid areas in Spain (Diez et al., 2000; Moreno et al., 1996) indicate that most N leaching occurs during periods of high irrigation or precipitation. The N leaching patterns are very different from those in more humid regions, where more N is leached during the winter than during the maize growing season due to high precipitation during the intercrop period of maize (Martinez and Guiraud, 1990; McCracken et al., 1994; Brandi-Dohrn et al., 1997).

There was a short lag between application of sidedress N to maize and an increase in N concentration in the leachate from the lysimeters. This is in agreement with Klocke et al. (1999) who reported reduced time lags for nitrate leaching when the soil was already wet, and explains the increases in NO_3^-–N concentration and N loads in drainage observed at the watershed scale after N side-dress applications in maize (Causapé et al., 2004; Isidoro et al., 2006).

Nitrogen leaching depends on the volume of drainage water and on the N concentration in drainage. Nitrogen leaching in maize has been mostly related to the volume of drainage whereas reductions in N concentration are not so often reported (Díez et al., 2000; Bjorneberg et al., 1996). Thus, reductions in the irrigation applied have been found to reduce N leaching but had detrimental effects on maize yield (Díez et al., 2000). Klocke et al. (1999) reported high N losses in maize under best management practices and concluded that it was difficult to reduce them. In this experiment, the use of barley or winter rape cover crops combined with a reduced N fertilizer rate to maize reduced N leaching in drainage water. The main factor determining the lower N leaching loads was the reduction in NO_3^-–N concentration in drainage water, as differences in the volume of drainage were minor. The reduction of NO_3^-–N concentration in drainage water was observed throughout the maize growing season, and not only at the start of irrigation or during winter. Given that an excess of irrigation water must be applied to leach salts, the use of a cover crop that reduces NO_3^-–N concentration is the best way to reduce N leaching while maintaining an adequate salt balance in the soil profile. A reduction in N leaching loads has been previously reported in maize with cereal cover crops, but it was observed primarily during winter time due to the higher drainage at this time (McCracken et al., 1994; Ball-Coelho et al., 2004; Martinez and Guiraud, 1990; Brandi-Dohrn et al., 1997).

The beneficial effects of legume cover crops on maize yields are well known but reports of their effect on N leaching are scarce. McCracken et al. (1994) found reduced N loads in drainage with a vetch cover crop compared to fallow, but this cover crop was not as effective as a rye cover crop for reducing N leaching. In our experiment the vetch cover crop received 50 kg ha^{-1} N less than the control but did not reduce N losses in drainage. This can be explained by the poor soil N depletion of this cover crop, the higher proportion of N supplied as N fertilizer and the faster N mineralization rate of a residue with a low C/N ratio (Cavero et al., 1997). Therefore, the general recommendation of using cover crops for reducing N leaching should be taken with care in case of a legume cover crop. According to this experiment, legume cover crops will not likely reduce N leaching especially when N fertilizer rates for the subsequent cash crop are not significantly reduced.

Under Mediterranean semiarid conditions the amount and distribution of rainfall are rather variable between years and the leaching of nitrate during the nongrowing season of maize can be very different. Previous experiments conducted in the same lysimeters showed that drainage volume during the maize intercrop period was low in 7 out of 9 yr and drainage was always higher during the maize growing season than in the intermaize periods. Cover crops have effectively reduced nitrate leaching under conditions of low risk, that is, in deep soils and low rainfall in the nongrowing season (≈64% of years). It is expected that N leaching reductions can be greater in conditions of high risk of N leaching. Thus, the behavior of cover crops should also be tested in years with greater rainfall in the nongrowing season, and in soils of intermediate and shallow depths, looking for additional abilities and drawbacks of cover crops to reduce nitrate losses in Mediterranean conditions.

CONCLUSIONS

The use of barley and winter rape as cover crops during the intercrop period of monoculture maize decreased maize yield by 2.7 Mg ha^{-1} when all the N in the cover crop was considered as available for the following maize crop and N fertilization reduced accordingly. Although maize yield grown after these cover crops was still high (14 Mg ha^{-1}), the reduction of maize yield was mainly explained by a slow N mineralization from the cover crops when maize had a high N demand, and by the low N content in the soil profile in spring after a cover crop. The use of vetch as a cover crop during the intercrop period of monoculture maize did not affect maize yield due to a higher N supply in this treatment.

Most N leaching occurred during the maize growing season. The use of barley and winter rape as winter cover crops and a reduced N fertilization to the subsequent maize crop effectively reduced N leaching in drainage by 80%. On the other hand, growing vetch as a winter cover crop did not reduce N leaching. The reduction in N leaching was mostly due to a reduction of NO_3^-–N concentration in drainage water and not to a reduction in drainage volume.

To use nonlegume winter cover crops to reduce N leaching it is necessary to consider that the mineralization of N from the cover crop biomass may not be sufficient to fulfill the following maize N requirement given the lower soil N content in spring after the cover crops.

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Capítulo 4

Effect of winter cover crop species and planting method on maize yield and N availability under irrigated Mediterranean conditions.

Capítulo 4: Effect of winter cover crop species and planting method on maize yield and N availability under irrigated Mediterranean conditions.

ABSTRACT

Under semiarid Mediterranean conditions irrigated maize has been associated to diffuse nitrate pollution of surface and groundwater. Cover crops grown during winter combined with reduced N fertilization to maize could reduce N leaching risks while maintaining maize productivity. A 2 year field experiment was conducted testing two different cover crop implantation methods (direct seeding after maize harvest versus cover crop seeding after conventional tillage operations) and five different cover crops treatments (barley, winter rape, oilseed rape, common vetch, and a control (bare soil)). Maize was fertilized with 300 kg N ha^{-1} at the control treatment, and this amount was reduced to 250 kg N ha^{-1} in maize after a cover crop. Direct seeding of the cover crops allowed earlier planting dates than seeding after conventional tillage, producing greater cover crop biomass and N uptake of all species in 2007 and of barley in 2008. Winter rape, oilseed rape and vetch biomass was reduced when direct seeded in 2008 due to a poor stand. Biomass N concentration in barley was much lower than in the other cover crops, resulting in higher C:N ratio (>25). Cover crops reduced the N leaching risks as soil N content in spring and at maize harvest was reduced compared to the control treatment. Maize yield was reduced by 4 Mg ha^{-1} after barley in 2007, and by 1 Mg ha^{-1} after barley and oilseed rape in 2008. The maize yield reduction was due to a N deficiency caused by insufficient N mineralization from the cover crops due to a high C:N ratio (barley) or low biomass N content (oilseed rape) and/or lack of synchronization with maize N uptake. SPAD measurements in maize leaves were useful to detect N deficiency in maize after cover crops. The use of vetch, winter rape and oilseed rape cover crops combined with a reduced N fertilization to maize was efficient for reducing N leaching risks while maintaining maize productivity. However, the reduction of maize yield after barley makes difficult its use as cover crop.

Keywords:

maize, cover crops, SPAD, direct seeding, tillage

Abbreviations:

DM, dry matter; HI, harvest index; KM, kernel mass; ET, evapotranspiration.

1. INTRODUCTION

Monoculture maize in semiarid conditions can be a high yielding crop (15 Mg ha^{-1} of grain), but has a high water and N input demand, with total plant N uptake of 300 kg N ha^{-1} and over (Berenguer et al., 2009; Moreno et al., 1996). Management of irrigation water and N fertilizer have been recognized as the main factors controlling N leaching risks and diffuse nitrate pollution of surface water and groundwater in irrigated semiarid areas (Isidoro et al., 2006; Causape et al., 2004; Cavero et al., 2003; Klocke et al., 1999; Diez et al., 1997; Pratt et al., 1989).

Reducing N fertilizer rates applied to maize can decrease N leaching risks and several works have studied the effect of N rates on the return flows from irrigated or rainfed fields (Diez et al., 2000; Sogbedji et al., 2000; Martin et al., 1994). However, due to the uncertainty for adjusting maize N fertilizer requirements under field conditions, often farmers apply N fertilizer rates that exceed maize N requirements in order to avoid risks of yield losses. Data from surveys in the Ebro River Basin (a semiarid irrigated area of Spain) indicate that rates of 318 - 453 kg N ha^{-1} yr^{-1} are applied every year by farmers (Isidoro et al., 2006; Cavero et al., 2003). When excess of N fertilizer is applied, residual N at harvest can be leached during the intercrop period of maize (October to April) (Moreno et al., 1996), depending on the unpredictable rainfall distribution under semiarid conditions. Moreover, N can be lost during the beginning of maize growing season when irrigation water applied exceeds crop evapotranspiration (Salmerón et al., 2010; Moreno et al., 1996).

N leaching risks also depend on irrigation management (Causapé et al., 2006; Cavero et al., 2003; Diez et al., 2000; Pang, et al., 1997; Schepers et al., 1995 ; Martin et al., 1994). Sprinkler irrigation allows high irrigation efficiencies, which can reach values close to 95% in sprinkler irrigated watersheds (Cavero et al., 2003), but some leaching fraction is generally needed in semiarid areas to prevent soil salinization problems in the long term (Oster, 1994). Surface irrigation systems usually result in lower irrigation efficiencies and higher N leaching losses (Isidoro et al., 2006).

Improving irrigation and N fertilizer management can reduce significantly N leaching losses (Diez et al., 2000). Adequately managed sprinkler irrigation combined with split N fertilizer applications should minimize N losses in maize, but results from monitored sprinkler irrigated watersheds indicate significant annual losses ranging from 25 to 50 kg N ha^{-1} (Cavero et al., 2003; Tedeschi et al., 2001). This suggests that adequate management of irrigation and N fertilizer should be complemented with other strategies to minimize N leaching.

Cover crops in humid climates are known to reduce N leaching during winter when precipitation is high (Tonitto et al., 2006; Ball-Coello et al., 2004; McCracken et al., 1994; Martinez and Guiraud, 1990). Growing winter cover crops before irrigated maize under semiarid conditions is not a common practice, as winter precipitation is usually low. However, cover crops have proved to be useful to avoid N leaching risks by depleting residual soil N and reducing N leaching at the start of irrigation and during maize growing season (Salmerón et al., 2010). Cover crops reduced nitrate concentration in drainage water, whereas drainage volume was unaffected during the maize growing season (Salmerón et al., 2010). This enabled a reduction in nitrate leaching while maintaining an adequate leaching fraction, which is a key factor to avoid salt accumulation in irrigated areas (Oster, 1994).

When winter cover crops are incorporated into the soil, part of the N contained in the cover crop residue can be mineralized (Stivers-Young, 1998) and available to the next cash crop. Therefore, the optimum N fertilizer rate to the subsequent maize crop should be reduced, as otherwise, N inputs in the system would be higher than without a cover crop, and it is likely that N losses would be greater in the long term (Hansen et al., 2000; Thomsen and Kristensen, 1999). In addition, a reduction of N fertilizer applied to maize will reduce total costs associated with cover crop management promoting their use by farmers. However, N fertilizer rates applied to maize after a cover crop should be well adjusted in order to avoid maize yield losses. Salmerón et al. (2010) found that maize grain yield can be reduced after non-legume cover crops in irrigated Mediterranean conditions because cover crop depleted the residual soil N after maize harvest but not all the N on the cover crops biomass was available for the following maize crop.

One constraint to the use of winter cover crops after maize is the short period of time available to plant the cover crop before frost. Direct seeding allows an early planting after maize harvest compared with conventional tillage and sowing. Besides, direct seeding reduces planting costs. However, emergence of small-seed cover crops such as brassicas could be hampered due to soil crusting and coarse maize crop residues in the field when direct seeding is used. Emergence of white mustard (*Sinapis alba* L.) cover crop has been reported to be affected by humidity and temperature, but not by reduced tillage and previous crop residues (Dorsainvil et al., 2005). It is important to evaluate cover crop growth under different sowing techniques and conditions in order to have a proper establishment of the cover crop.

The objectives of this study were: (1) to quantify the biomass and N uptake of different winter cover crops with two planting methods in a monoculture maize system under irrigation (2) to evaluate the effect of these cover crops on soil N dynamics, soil water content, and maize yield.

2. MATERIALS AND METHODS

Site and experimental design

The experiment was carried out from 2006 to 2008 in an experimental field at the Estación Experimental de Aula Dei (CSIC) located in the Ebro Valley (41º43'N; 0º49'W, 225 m altitude) in Zaragoza, Spain. The climate is Mediterranean semiarid with mean annual maximum and minimum daily air temperatures of 20.9 and 8.5ºC, respectively, yearly average precipitation of 322 mm, and yearly average reference evapotranspiration of 1,100 mm. The soil is a clay loam (27% sand, 51% silt and 26% clay) classified as Typic Xerofluvent (Table 1). The field was cropped with maize during three years previous to the start of the experiment.

The experimental design was a split plot with two factors and 3 replicates. The main factor studied was the planting method of the cover crops: direct seeding after maize with no-tillage (DS) or soil preparation with common tillage operations after maize harvest and before cover crop sowing (CT). The second factor studied was the different winter cover crop species: winter barley

(*Hordeum vulgare cv.*Hispanic), common vetch (*Vicia sativa cv.* Armantes), winter rape (*Brassica rapa cv.* Perko), oilseed rape (*Brassica napus cv.* Madrigal), and a control treatment with bare soil during winter. The size of each experimental plot was 6 m by 18 m.

Table 1. Soil characteristics of the experimental field.

Depth	pH	C	N	$CaCO_3$	Sand	Silt	Clay	FC	WP
m		---------------------------------			%	---------------------------------		----- m^3	m^{-3} ----
0.0 - 0.3	8.4	0.86	0.110	30.9	26.5	45.4	28.1	0.351	0.197
0.3 - 0.6	8.4	0.72	0.102	31.6	24.0	46.9	29.1	0.351	0.217
0.6 - 0.9	8.4	0.44	0.088	30.7	17.4	50.0	32.6	0.344	0.196
0.9 - 1.2	8.6	0.38	0.075	30.3	19.1	50.3	30.6	0.329	0.171

FC: Field capacity (-0.033 MPa)
WP: Wilting point (-1.5 MPa)

Maize grain was harvested each year with a combine that chopped the maize stubble and left it on the soil. In the DS treatment maize residue was left on the soil surface, whereas in the CT treatment it was incorporated immediately after maize harvest with a disc harrow. Cover crops were sown with a commercial seed drill (SD-1203, Solá, Calaf, Spain) as soon as possible after maize harvest (Table 2), at seeding rates of 180, 12, 7 and 110 kg ha^{-1} for barley, winter rape, oilseed rape and common vetch, respectively. In the DS treatments cover crops were sown directly, whereas in the CT treatments, seedbed was prepared with a stubble cultivator before sowing. In the control treatment, the same soil tillage practices than for the cover crop treatments were implemented within each planting method studied. Some irrigation was provided (40 mm in 2006 and 51 in 2007) after the winter cover crop sowing to ensure its emergence. In the following spring after cover crop growth in 2007 and 2008, the cover crops were mechanically incorporated into the soil with a power tiller (Table 2).

Maize cultivar 'Pioneer PR34N43' was planted on the reported dates in Table 2 at a plant density of 87,000 plants ha^{-1}. Maize was fertilized with 300 kg N ha^{-1} in the control treatment and this rate was split in three equal applications (100 kg N ha^{-1}): at pre-plant as urea (46% N), and two side-dress applications as ammonium nitrate (33.5% N) at V6 and V12 growing stages. In the cover crop treatments pre-plant N application was reduced to 50 kg N ha^{-1}. P and K were applied before maize planting at a rate of 100 and 150 kg ha^{-1} of P_2O_5 and K_2O, respectively.

Maize was irrigated using a solid set sprinkler irrigation system with spacing of 18 m x 18 m obtaining an application rate of 5 mm h^{-1}. Previous studies in the same field reported a high irrigation uniformity close to 90% (Cavero et al., 2008). The weekly irrigation requirements were calculated from the daily ETo (estimated with the Penman-Monteith equation) and the crop coefficients, according to the FAO procedures (Allen et al., 1998) and considering an irrigation efficiency of 85%. The volume of irrigation applied was measured with an electromagnetic flow meter (Promag 50, Endress+Hauser, Reinach, Switzerland) which has a measurement error of ± 0.5%. Total water applied as irrigation plus precipitation during maize growing season was 890 and 750 mm for 2007 and 2008, respectively. Weed and pest control was made according to the standard practices of the area to ensure an adequate growth of the maize crop.

Table 2. Dates of cover crop and maize sowing time, cover crop incorporation and maize harvest.

Operation	Date	
	2007	2008
Cover crop		
Sowing (DS)	3 Nov. 2006	30 Oct. 2007
Sowing (CT)	15 Nov 2006	7 Nov. 2007
Incorporation	12 Apr. 2007	7 Apr. 2008
Maize		
Sowing	8 May 2007	25 Apr. 2008
Harvest	23 Oct. 2007	24 Oct. 2008

DS: cover crop direct seeded after maize harvest
CS: cover crop seeded after conventional tillage operations

Cover crops and maize growth analysis.

Cover crops were sampled before being incorporated into the soil by harvesting the aboveground biomass contained in 1 m^2. Leaf area was measured with a leaf area meter (LI-3000, LI-COR, Lincoln, USA). The sample was then oven dried at 65ºC, weighed and finely ground before total N and C analysis by combustion (TruSpec CN, LECO, St. Joseph, MI, USA).

Leaf greenness of maize was measured during the growing season with a chlorophyll meter (SPAD-502, Minolta Camera Co., Ltd., Japan). Measurements were done on the youngest fully developed leaf until the silks emerged and later on the ear leaf. The average from 30 readings in different plants within each plot was calculated.

Maize was harvested on the dates reported in Table 2. All the ears in 2 rows of 10 m length per plot were hand harvested to determine yield, number of grains per square meter, and unit kernel mass (KM). The plants contained in a 2 rows x 2 m section were harvested and the grain was separated from the rest of the plant. Grain and plants were dried at 65ºC, weighed and ground prior to analyses of total N and C similarly to the cover crops biomass. Grain yields are reported on the basis of 140 g kg^{-1} moisture content.

Maize stalks to evaluate the end-of-season nitrate test were collected at harvest time from 15 plants following the procedure described by Binford et al. (1992). In all cases the sheaths were removed from the stalks, then oven dried at 65 ºC and ground. A subsample of 2 g was extracted with 50 mL of KCl 2N, shaken for 30 min, filtered through a cellulose filter (Whatman no. 1) and analyzed with a continuous flow analyzer by spectrophotometry UV-Vis (THERMO-OPTEK, Iris Advantage Ers Duo*,* Thermo Fisher Scientific, Massachusetts, USA).

Soil analysis

Soil was sampled each year before cover crop incorporation and after maize harvest. Two soil cores from each experimental plot were taken with a 5 cm diameter hand auger (Eijkelkamp Agrisearch Equipment BV, The Netherlands) and the two samples were combined per depth in 0.3 m increments to 1.2 m depth. In the second year, soil was sampled to 2.1 m depth with an auger coupled to a tractor and soil samples were combined in 0.3 m increments as well. The soil was fresh-sieved to pass a 2 mm sieve, and 10 g were extracted with 30 ml of KCl 2N solution for determination of NO_3^--N and NH_4^+-N concentrations colorimetrically with a continuous flow analyzer (AA3, Bran+Luebbe, Norderstedt, Germany). Another subsample was dried at 105ºC to constant weight for gravimetric water content determination. Gravimetric water content was converted to volumetric water content using a bulk density of 1.46 g cm^{-3}, obtained from previous studies in the same experimental field.

A N budget was calculated for the maize crop period considering the 0 to 1.2 m soil layer. Inputs considered were soil mineral N before cover crop incorporation ($N_{inorg\ I}$) and N applied as fertilizer (N_F). Outputs included were soil mineral N at maize harvest ($N_{inorg\ H}$) and maize N uptake (N_{uptake}). Soil mineral N is the sum of NO_3^--N and NH_4^+-N. The unbalance term

(ΔN) of equation (1) would include N mineralization – N losses by drainage leaching and by volatilization and denitrification. N mineralization include soil, maize stover and cover crop biomass net mineralization.

$$\Delta N = N_{inorgH} + N_{uptake} - N_{inorg\ I} - N_F \qquad [1]$$

A N budget was calculated similarly for the intercrop period considering the 0 to 1.2 m soil layer. The soil mineral N after maize harvest of previous year (N_{inorgH}) was considered as input. Outputs included were soil mineral N before cover crop incorporation ($N_{inorg\ I}$) and cover crop N uptake ($N_{cc\text{-}uptake}$). The unbalance term (ΔN) of equation (2) would include N mineralization – N losses by drainage leaching and by volatilization and denitrification. N mineralization include soil and maize stover net mineralization.

$$\Delta N = N_{inorgH} + N_{CC-uptake} - N_{inorg\ I} \qquad [2]$$

Statistical analysis

Data were analyzed using analysis of variance through the General Linear Model (GLM) procedure of the SAS 9.1 software (SAS Institute, 2004). Multiple comparisons among treatments were performed using Fisher's Protected LSD test at P = 0.05. Values of soil N_{inorg} and maize stalk NO_3^--N were transformed prior to analyses by the function y=log(x) to obtain homogeneity of variance.

3. RESULTS

Cover crop aboveground biomass and N uptake

Cover crop aboveground biomass in 2007 ranged from 731 to 6,993 kg ha^{-1}, and was affected by the planting method and by the cover crop treatment, but it was not affected by the interaction of the two factors studied (Table 3). The earlier planting date in DS treatment produced higher cover crop biomass compared to CS (1.7 Mg ha^{-1} higher averaging over cover crops). Barley produced the highest cover crop biomass, which was more than double than the other cover crops. In 2008, cover crop biomass was lower in general, ranging from 427 to 3,148 kg ha^{-1}, and the interaction of the planting method and the cover crop treatment was significant. Direct seeded barley produced higher biomass than the other cover crop species independently of the planting method. However, the biomass of barley was not significantly affected by the planting method. Winter rape and vetch with conventional planting had similar biomass productions than barley CS, whereas the rest of the cover crops and planting methods had significantly lower biomass productions (< 1 Mg ha^{-1}).

In 2007 N uptake of cover crops ranged from 18 to 116 kg N ha^{-1} and was affected by the planting method and almost by the cover crop species (P=0.0531). The earlier sowing time with direct sowing (12 days early) allowed a greater accumulation of N in the aboveground biomass of the cover crops this year (50 kg N ha^{-1} more). Barley had a tendency to produce the highest N uptake in 2007, followed by winter rape, vetch and oilseed rape. N uptake of cover crops in 2008 was lower than in 2007 and was not affected by the planting method or the cover crop species.

In 2007, N concentration in the cover crop plants was only affected by the cover crop species, whereas in 2008 was affected by the cover crop*planting method interaction. In both seasons, barley had a lower N concentration (average of 1.5%) compared to the other cover crops (average of 3.1%). Oilseed rape, winter rape and vetch had similar concentrations in 2007, whereas in 2008 winter rape CS had a lower N concentration than the other cover crops species. The C:N ratio had a similar response than N concentrations. Barley presented C:N ratios higher than 27 (average of 31) whereas the other species had values lower than 20 (average of 14).

Table 3. Cover crop aboveground biomass, N uptake and concentration, and C/N ratio before incorporating the cover crops into the soil in spring depending on planting method and cover crop treatment during the two years of the experiment.

Treatments	Biomass		N Uptake		N Concentration		C:N ratio	
	2007	2008	2007	2008	2007	2008	2007	2008
	------------------ kg ha^{-1}		------------------		-------- %	---------		
Planting method (P value)	*0.018*	*NS*	*0.043*	*NS*	*NS*	*NS*	*NS*	*NS*
Direct seeding (DS)	3854 a	1208	101 a	34	2.90	2.36	16.7	22.8
Conventional seeding (CS)	2104 b	1557	49 b	35	2.58	2.40	17.4	22.1
Cover crop species (P value)	*0.001*	*0.001*	*0.053*	*NS*	*0.001*	*0.001*	*0.001*	*0.001*
Barley	5555 a	2668	93	35	1.68 b	1.26	27.1 a	35.8
Oilseed rape	1962 b	482	61	21	3.08 a	3.00	12.8 b	13.5
Winter rape	1765 b	1339	80	32	3.44 a	2.47	13.5 b	17.6
Vetch	2228 b	1041	72	52	3.14 a	3.44	13.0 b	12.6
Planting method * Cover crop species (P value)	*NS*	*0.031*	*NS*	*NS*	*NS*	*0.015*	*NS*	*0.017*
Barley DS		3148 a				1.42 d		32.8 b
Barley CS		2187 ab				1.09 d		38.8 a
Oilseed rape DS		427 d				-		-
Oilseed rape CS		536 cd				3.00 b		13.5 d
Winter rape DS		715 cd				3.42 a		11.7 e
Winter rape CS		1963 b				1.99 c		20.6 c
Vetch DS		540 cd				3.23 a		13.4 de
Vetch CS		1542 bc				3.59 a		12.1 de

DS: cover crop direct seeded after maize harvest
CS: cover crop seeded after conventional tillag operations

Maize grain yield, yield components and N uptake

Maize grain yield and yield components were affected by the cover crop treatment but not by the cover crop planting method or by the interaction of the two factors. For this reason, only the cover crop treatments results are presented in Table 4. In 2007, the barley cover crop decreased the maize grain yield by 3.9 Mg ha^{-1} compared to the control (Table 4). The other cover crop treatments produced similar maize grain yield than the control. In 2008, the barley and oilseed rape cover crops slightly decreased (≈ 1 Mg ha^{-1}) the maize grain yield compared to the control, but the winter rape and common vetch treatments produced a similar maize grain yield than the control.

Table 4. Maize grain yield (at 140 g kg^{-1} moisture content), total aboveground biomass, harvest index (HI), kernel mass (KM), grain number per m^2, stalk NO_3-N, N concentration in grain and plant, and N uptake in grain and plant for each cover crop treatment and year. The planting method and the interaction of planting method and cover crop treatment were not significant (P>0.05).

						N concentration		N uptake		
Cover crop treatment	**Grain**	**Total biomass**	**HI**	**KM**	**Grains m^{-2}**	**Grain**	**Plant**	**Grain**	**Total**	**Stalk NO_3^--N**
	------- Mg ha^{-1} ------			g unit^{-1}		--------- % ---------		-------- kg ha^{-1} ------		**mg kg^{-1}**
					2007					
Control	15.6 a	26.7 a	0.52	0.373 a	3709 a	1.32 ab	0.70 a	181 ab	272 ab	1081 ab
Barley	11.7 b	20.7 c	0.49	0.337 b	3048 b	1.16 c	0.54 b	121 c	178 c	35 c
Oilseed rape	15.1 a	25.5 ab	0.52	0.389 a	3444 a	1.29 b	0.76 a	172 b	265 ab	500 b
Winter rape	14.6 a	24.7 b	0.52	0.374 a	3459 a	1.25 bc	0.65 ab	162 b	240 b	761 ab
Common Vetch	15.7 a	26.7 a	0.53	0.391 a	3560 a	1.42 a	0.68 a	197 a	285 a	1071 a
P value	0.001	0.001	NS	0.003	0.006	0.003	0.020	0.001	<0.0001	0.001
					2008					
Control	14.6 a	24.1	0.53	0.371	4469 a	1.43	0.83 a	183	277 a	1328 a
Barley	13.7 bc	22.2	0.54	0.381	4081 b	1.33	0.70 bc	161	232 c	469 c
Oilseed rape	13.6 c	21.8	0.55	0.371	4148 b	1.36	0.70 bc	163	232 c	808 bc
Winter rape	14.0 abc	22.4	0.55	0.373	4252 ab	1.42	0.68 c	174	244 bc	794 bc
Common Vetch	14.4 ab	22.9	0.55	0.393	4167 b	1.39	0.77 ab	176	255 b	984 ab
P value	0.035	NS	NS	NS	0.018	NS	0.014	NS	0.002	0.001

Total aboveground biomass of maize was significantly reduced in the barley and winter rape treatments compared to the control (6 and 2 Mg ha^{-1} less, respectively) during the 2007 season (Table 4). In the subsequent year the aboveground biomass was not affected by the cover crop treatment. The cover crop treatments did not affect the harvest index of maize (Table 4). In 2007, the kernel mass and the number of grains per m^2 were only significantly reduced after the barley cover crop. In 2008, the kernel mass was not affected by the cover crop treatment.

In 2007, grain and plant N concentration were significantly lower in maize after barley compared to the control. The maize grain N concentration was higher in the vetch treatment compared to the other cover crop species. In 2008, grain N concentration was not affected by the cover crop treatment, but plant N concentration was reduced in maize after barley, oilseed rape and winter rape compared to the control. Similarly to grain N concentration, grain N uptake was reduced in maize after barley in 2007 compared to the control, and was higher in the vetch treatment compared to the other cover crop species. In 2008, grain N uptake was not affected by the cover crops. Pooling data from both years, grain N uptake was better correlated (R^2=0.83) with grain yield than with grain N concentration (R^2=0.70). Compared to the control, total N uptake (grain + plant) was greatly reduced in maize after barley in 2007 (94 kg N ha^{-1} less than the control), and in a lesser extent in all the cover crop treatments in 2008 (20 – 40 kg N ha^{-1} less than the control). The vetch cover crop treatment had a higher total N uptake than the other cover crop species with the exception of winter rape in 2008, which had similar total N uptake.

Corn stalk nitrate concentrations at harvest were significantly lower than the control in the barley cover crop treatment in 2007, and in the barley, oilseed rape and winter rape cover crops treatments in 2008 (Table 4).

The SPAD readings of maize leaves were not affected ($P>0.05$) by the cover crop planting method. There was a significant effect of cover crop treatments on SPAD although the results were different depending on the year and date of measurement (Table 5). SPAD values in 2007 were lower in maize after barley and winter rape at the V8 maize stage. At the V14 stage there were no differences between treatments, whereas at flowering (R1) and maturity (R5) SPAD values in maize after barley were lower than the other treatments. In 2008, SPAD values were in general lower than the control in maize after barley, oilseed rape and winter rape at the V6 and V10 stages, but no significant differences were found at the V12 stage or later. The regression of SPAD values measured at the R1 stage with relative grain yield showed a significant relationship in 2007 (R^2=0.71; $P<0.001$), but not in 2008 (R^2=0.12; P=0.066) (Figure 1).

Table 5. Average SPAD values of maize leaves in the different cover crop treatments during the maize growing season in 2007 and 2008. Values followed by the same letter are not significantly different (P>0.05). The planting method and the interaction of planting method and cover crop treatment did not affect the SPAD variable.

Cover Crop treatment	SPAD					
	2007					
	V8		**V14**		**R1**	**R5**
Control	50.7 ab		49.7		57.4 a	56.4 a
Barley	42.4 d		47.7		54.8 b	46.9 b
Oilseed rape	49.0 bc		48.9		57.5 a	55.6 a
Winter rape	48.1 c		49.6		56.8 a	54.2 a
Vetch	52.5 a		49.0		57.7 a	55.5 a
P value	0.001		NS		0.001	0.001
	2008					
	V6	**V10**	**V12**	**V15**	**R1**	**R5**
Control	41.4 a	52.5 a	51.4	44.1	57.7	57.9
Barley	37.3 c	50.8 c	52.1	44.7	57.8	55.9
Oilseed rape	40.1 ab	51.3 bc	50.6	44.0	56.5	56.0
Winter rape	39.7 b	51.9 ab	51.6	44.6	58.2	56.1
Vetch	41.0 ab	52.0 a	52.2	44.7	57.3	57.0
P value	0.001	0.001	NS	NS	NS	NS

V6: 6 leaves stage; V8: 8 leaves; V10: 10 leaves; V12: 12 leaves; V14: 14 leaves; R1: silking; R5: dent.

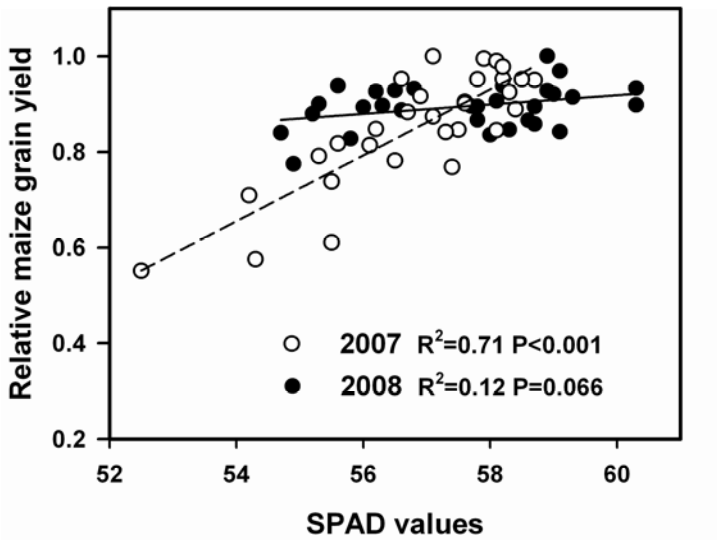

Figure 1. Relationship between relative maize grain yield and SPAD values of maize leaves at silking (R1) in 2007 and 2008. For each year, data from all treatments were pooled (n=30).

Soil water content

Soil water content in spring before incorporating the cover crops was affected by the cover crop treatment but not by the planting method (Figure 2). Cover crops reduced soil water content compared to the control in both years, as revealed by contrast of significance of control vs. cover crop treatments ($P<0.05$ in 2007; $P<0.001$ in 2008). The differences of available water with the control treatment after the cover crops in the whole soil profile (0-1.2 m depth) ranged from 6 mm (oilseed rape) to 14 mm (barley) in 2007 due to the heavy rains prior to cover crop incorporation. In 2008, decreases in soil available water compared to the control were higher: 35, 3, 9 and 14 mm after barley, oilseed rape, winter rape, and vetch in 2008, respectively. Barley was the cover crop that removed more soil water both years, as deep as 1.2 m in 2007 and 0.9 m in 2008 (Figure 2a and c) which is consistent with the higher biomass production of this cover crop (Table 3). Vetch reduced soil water content to 1.2 m soil depth in 2007 but to a lower depth (0.6 m) in 2008. Oilseed rape reduced soil water content in the 0 to 0.6 m soil layer in 2007, and winter rape in the 0 to 0.3 m soil layer in 2008.

At the beginning of maize growing season (around V6 stage), soil water content was similar for all treatments in the 0-30 cm soil layer (data not shown). Similarly, no differences in soil water content were found at maize harvest in all the soil profile (Figure 2 b and d).

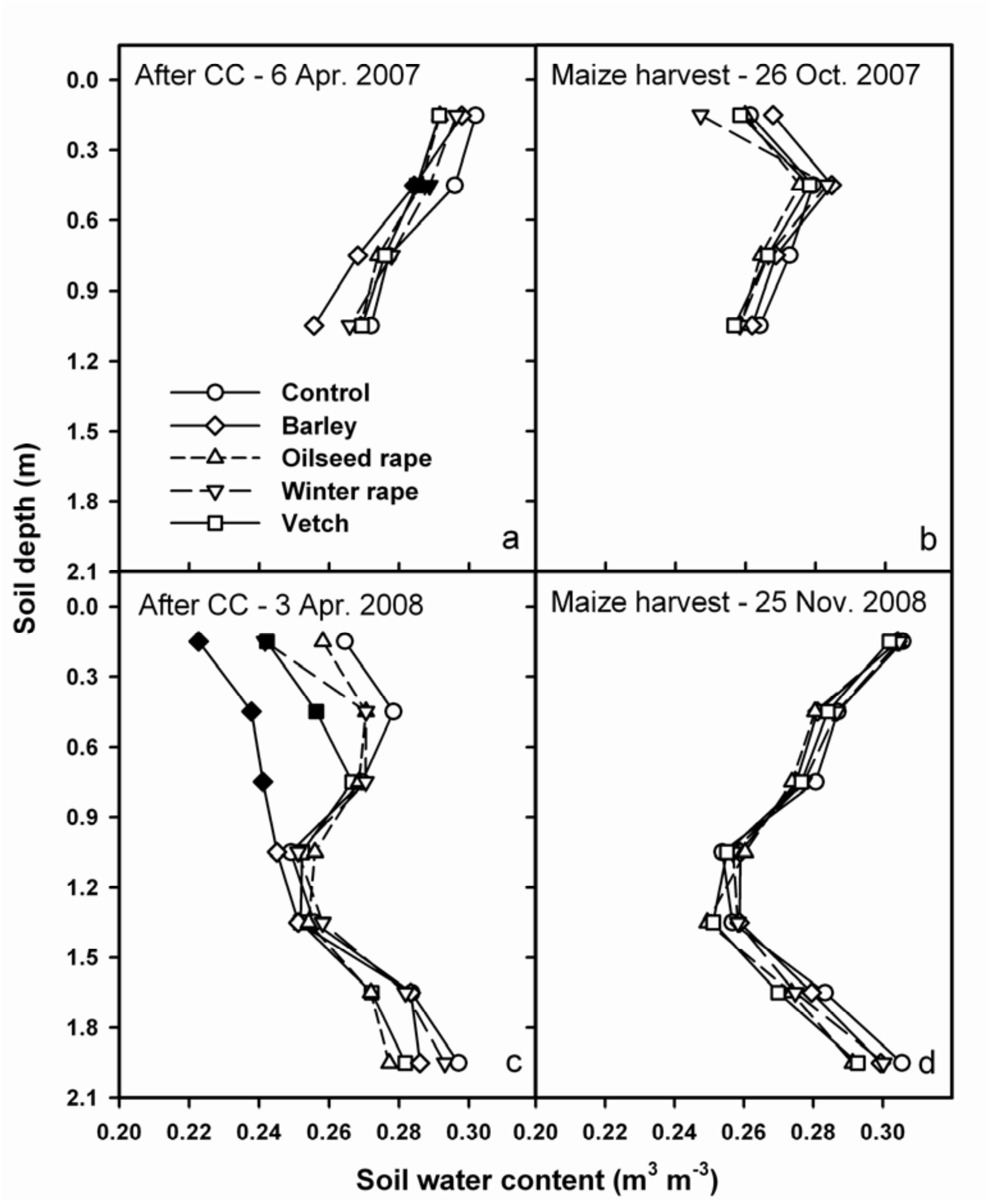

Figure 2. Soil water content in the soil profile after the cover crops (CC) and before being incorporated (a and c) and at maize harvest (b and d) in the two years of the experiment. The closed (black) symbols indicate significant differences compared to the control treatment within each soil depth at P<0.05 after ANOVA.

Soil mineral N and N balance

Soil inorganic N in spring, before incorporating cover crops into the soil, was affected by the cover crop planting method depending on the cover crop treatment. This interaction is explained because the oilseed rape treatment in spring 2007, and the oilseed rape and vetch in 2008, had a greater soil N depletion when the cover crops were seeded with conventional tillage than when direct seeded, probably due to a poor establishment of these cover crops when direct seeded. Because this effect of cover crops planting method in soil inorganic N content was relatively small and associated to the indirect effect on cover crop establishment, the average values of the different cover crop treatments are presented in Figure 3 and Table 6.

Table 6. Soil inorganic N (N_{inorg}) measured before incorporating the cover crops in spring and at maize harvest, at different soil layers in the cover crop treatments.

Cover crop treatment	Soil N_{inorg} before incorporating cover crops			Soil N_{inorg} after maize harvest		
	2007	2008		2007	2008	
	0-1.2 m	0-1.2 m	1.2-2.1 m	0-1.2 m	0-1.2 m	1.2-2.1m
	-- kg ha^{-1} --					
Control	202 a	105 a	79	202 a	66 a	52
Barley	90 b	34 b	57	98 b	38 b	29
Oilseed rape	134 ab	73 a	62	128 ab	46 ab	41
Winter rape	157 a	73 a	73	119 ab	50 ab	49
Vetch	131 ab	70 a	59	160 ab	57 a	45
P value	0.057	0.006	NS	0.093	0.067	NS

In 2007, barley, oilseed rape and common vetch reduced significantly the soil N_{inorg} to 0.6 m depth in spring before its incorporation to the soil (Figure 3a). In 2008, barley and winter rape reduced soil N_{inorg} significantly to the 0.6 m depth (Fig. 3c). Soil N_{inorg} content below this depth was also on average lower when a cover crop was grown compared to the control, although not significantly. Considering the soil profile up to 1.2 m, barley reduced soil mineral N compared to bare soil in 112 and 71 kg N ha^{-1} in 2007 and 2008, respectively. The other cover crops reduced soil N_{inorg} to a lesser extent and not statistically significant, on average 60 kg N ha^{-1} in 2007 and 33 kg N ha^{-1} in 2008 (Table 6). Soil inorganic N in the 1.2 to 2.1 m layer in the second year of the experiment was not significantly different between treatments in spring. However, the soil inorganic N in this layer was on average 21 kg N ha^{-1} lower after the barley and vetch cover crops compared to the control.

At maize harvest, the soil N_{inorg} content in the soil profile was similar for all the treatments where cover crops were grown (Figure 3 b and d), except for a reduced soil N content in the 0.3 to 0.6 m soil layer compared to the control in 2007 (Figure 3 b). Considering all the soil profile (0 to 1.2 m depth), soil inorganic N had a tendency to be lower after a cover crop compared to the control, but this was not statistically significant (Table 6). Soil N_{inorg} content after the barley cover crop treatment was on average 104 and 28 kg N ha^{-1} lower in 2007 and 2008, respectively. The other cover crop species also had lower soil N_{inorg} after maize harvest compared to the control but to a lesser extent.

Plant available N for maize, estimated as soil N_{inorg} at pre-plant in the 0 to 0.9 m soil layer plus N applied as fertilizer, was not related to maize grain yield in 2007 (R^2=0.32, NS) but it was related significantly in 2008 (R^2=0.47, P=0.0289) (Figure 4 a and b).

During the first intercrop period there was a positive N balance (net N mineralization – N losses) ranging from 26 to 63 kg/ha (Table 7) and without significant differences between the cover crop treatments. However, during the second intercrop period there was a negative N balance (N immobilization or N lost), but similarly no statistically differences were found between the cover crops treatments. During the first maize crop period only the vetch treatment showed a significant positive balance, while the other treatments showed a negative one or close to 0 (oilseed rape). During the second maize crop period there was a slight negative balance in the control treatment while there was a small positive balance when a cover crop was grown (except in oilseed rape).

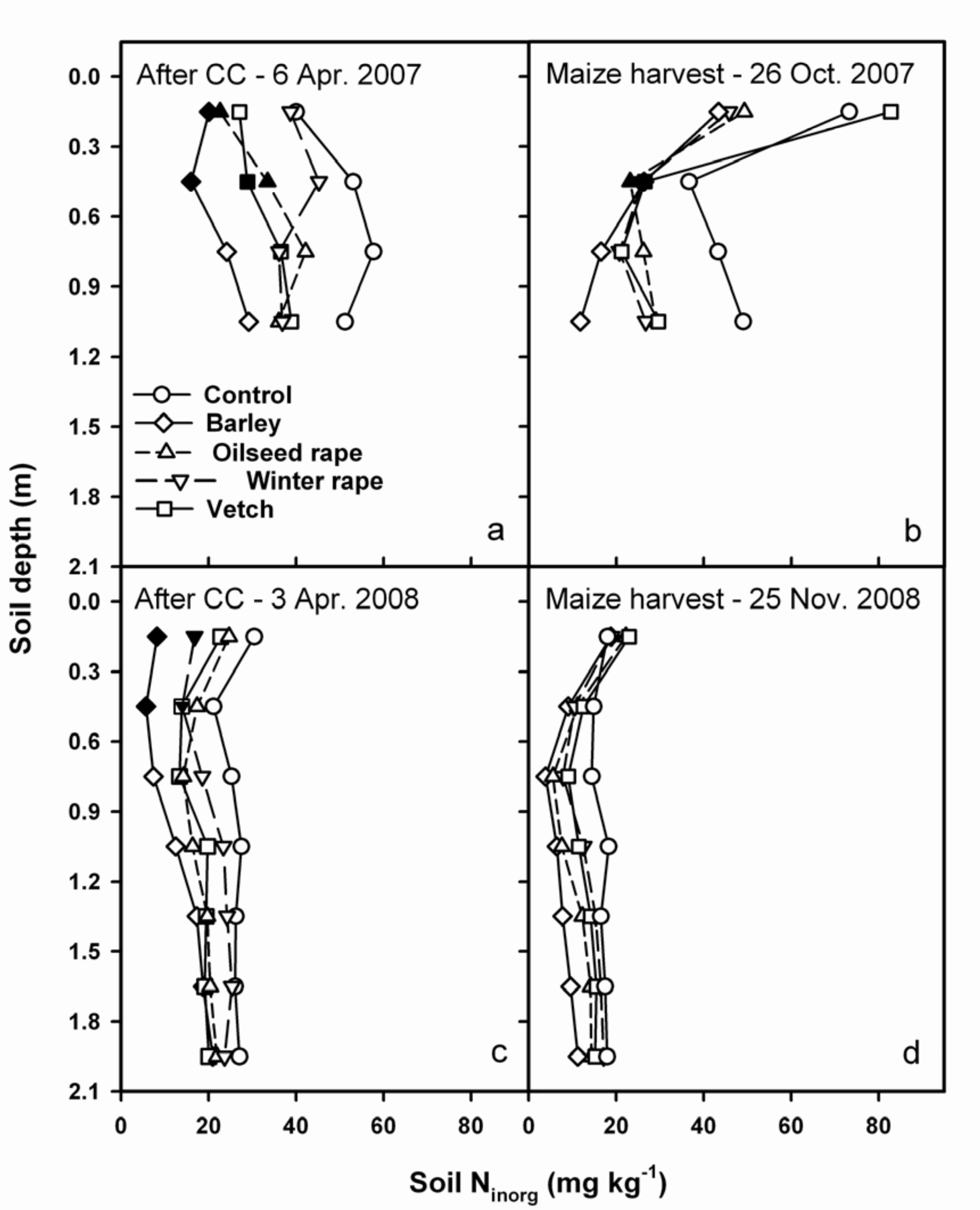

Figure 3. Soil mineral N (Ninorg) in the soil profile before the incorporation of the cover crops (CC) in spring (a and c) and at maize harvest (b and d) in the two years of the experiment. The closed (black) symbols indicate significant differences compared to the control treatment within each soil depth at P<0.05 after ANOVA.

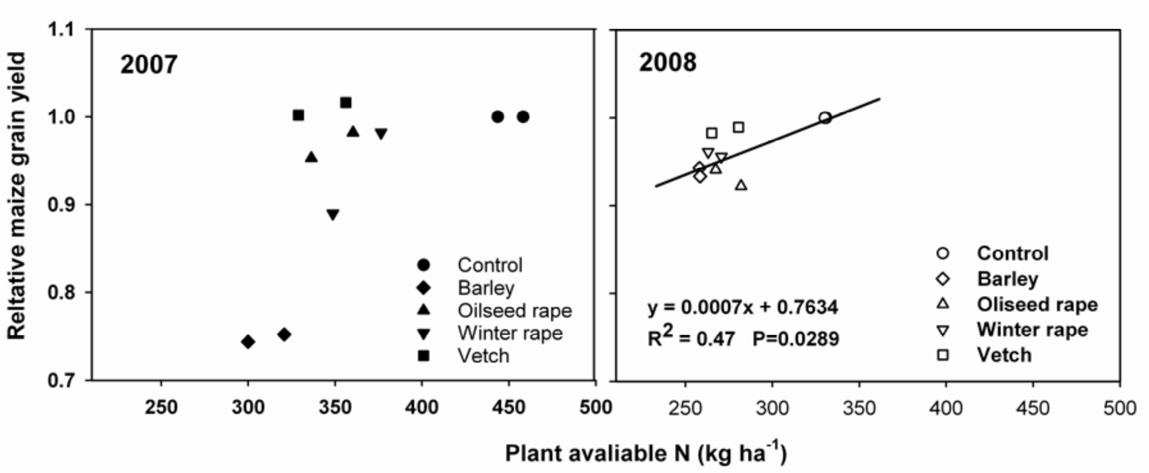

Figure 4. Relationship between relative maize grain yield and plant available N (Soil N_{inorg} before sowing + N fertilizer) in 2007 and 2008 averaged for each cover crop treatment and cover crop sowing method.

Table 7. N balance during the maize croping season and during the intercrop cropping season . ΔN symbolizes the unbalance term of the balance (net N mineralization – N losses).

Cover crop treatment	ΔN Intercrop period (kg ha^{-1})	ΔN Maize crop (kg ha^{-1})	
	2007		
Control	63	-28	a
Barley	26	-63	a
Oilseed rape	31	9	ab
Winter rape	33	-40	a
Vetch	45	63	b
P value	NS	0.036	
	2008		
Control	-98	-10	
Barley	-29	15	
Oilseed rape	-41	-3	
Winter rape	-14	20	
Vetch	-56	36	
P value	NS	NS	

4. DISCUSSION

Cover crop growth as affected by planting method and species

Growing a cover crop after maize harvest is not common in the irrigated areas of the Ebro River Basin and other semiarid irrigated areas in Spain. This is partly due to the limited information available about how to manage the cover crops and the suitability of the different species as winter cover crops. In one of the two years all cover crops studied produced biomass and aboveground N content in the high range of those reported under other conditions (Kramberger et al., 2009; Maltas et al., 2009; Thomsen, 2005; Stenberg et al., 1999). The relatively wide maize intercrop period from October - November to March enabled the cover crops to grow significantly and without high supplemental irrigation (40 to 51 mm), making this practice a possible option in the study area.

Direct seeding of the cover crops enabled to plant them 8 to12 days earlier compared to seeding after conventional tillage operations. Earlier sowing dates have been reported to increase cover crop growth and N uptake (Stenberg, 1998). This was in agreement to the first year of the experiment when direct seeding of cover crops allowed earlier sowing time and resulted in higher cover crop biomass productions and N uptake. However, direct seeding had a detrimental effect on common vetch, oilseed rape and winter rape in 2008, which resulted in a poorer establishment compared to conventional seeding. This could be explained by a poorer emergence due to the maize stover residue which mechanically hampered plant emergence of these species. Optimum sowing date for brassicas and vetch in the area when grown as cash crops is one month earlier than the planting date used in the experiment, and this could also explain the poor growth of these crops. Barley was the cover crop that produced more biomass, probably due to the fact the planting date was optimal for this species in the area and the higher initial vigor of barley compared to the other species.

Although barley ensures a good plant establishment and high biomass it always resulted in lower biomass N concentration and higher C:N ratio compared to the other cover crop species. The high C:N ratio in barley (ranging from 26 to 39) increases the risk of N immobilization processes when it is incorporated to the soil, as C:N ratios above 25 have been related to N immobilization (Kuo and Jellum, 2000; Kaye and Hart, 1997; Ranells and Wagger, 1996). Winter rape, oilseed rape and vetch had a lower C:N ratio (ranging from 11 to 20), but can only produce significant biomass and N accumulation provided there is a good crop establishment. The reasons for the poor stand in these cover crops in some years should be better studied, as well as other possible cover crop species with a better implantation and higher N concentration (and lower C:N ratio) in plant biomass than barley. Anyhow, N concentrations and C:N ratios of cover crops tested were much favorable for N mineralization than those reported by Kramberger et al. (2009) for Italian ryegrass, winter rape and different legumes.

The cover crop planting method had no significant effect on soil N dynamics and maize grain yield response and, therefore, only the effect of the cover crop factor is discussed in the subsequent discussion sections.

Cover crop effect on soil water content and N dynamics.

The lower soil water content in spring after the cover crops compared to bare soil was the result of cover crop transpiration. In the first year of the experiment, the high rainfall during cover crop growing season (241 mm), with high precipitation events in spring close to the time of cover crop incorporation was the reason for the similar soil water contents after the cover crop growth compared to the control (bare soil). However, in the second year the reduction of soil water content due to the cover crop transpiration was high due to the lower rainfall during all cover crop growing season (92 mm). Even though the irrigation applied to the maize crop was the same in all cover crop treatments, the similar soil water content at the V6 maize stage and at harvest in all treatments indicates that the cover crop growth did not reduce significantly the available water for the maize crop, as soil water differences were small and probably disappeared with the start of irrigation.

Cover crops reduced significantly soil N_{inorg} content in spring compared to bare soil up to 0.6 m soil depth, and soil N below this layer also had a tendency to be lower after a cover crop. Deeper soil N depletions were expected for the brassicas species, as has been previously reported (Thorup-Kristensen, 2001). However, the poor establishment of the brassica crops and the late sowing date could explain the relatively low soil N depletion compared to barley. The highest soil N depletions observed after barley can be explained by the higher biomass production and high N uptake in this cover crop. These soil N reductions can avoid N leaching during winter with occasional heavy precipitations that can occur in semiarid conditions during this time, such as in March-April 2007 (184 mm). Furthermore, cover crop transpiration resulted in lower soil water content in early spring in one of the years, which will reduce drainage and the associated N leaching risks during the first irrigation events in the next maize crop (Salmerón et al., 2010).

At maize harvest, the reduction of soil inorganic N content observed after the cover crop treatments reduces N leaching risks. Residual N_{inorg} at harvest can be lost during the next intercrop period, or with irrigation during the beginning of the next maize growing season, when the maize plants have not fully developed their root system. Deep placed soil N_{inorg} is more likely to be moved below the next crop root depth and therefore lost by leaching. Subsoil N content (below 1 m) has proved to be useful to indicate differences among treatments in N leaching losses under more humid conditions (Thorup-Kristensen et al., 2009). However, no differences were found below 1.2 m soil depth in our experiment. Recent studies (Salmerón et al., 2010) under irrigated conditions similar to this experiment found that most N leaching occurs during maize growing season with the first irrigations, and that the movement of nitrate through the soil profile could be too fast to be detected at maize harvest, even at the deep soil profiles studied in 2008. This is in agreement with the increases of nitrate in drainage water observed after side-dress N applications in watershed studies (Isidoro et al., 2006; Causapé et al., 2004) in the same area. Consequently, the reduction in soil N_{inorg} content in spring before the start of irrigation could be the most limiting factor determining N leaching losses under irrigated conditions. A cover crop that depletes residual soil N after maize harvest and a proper N fertilization management to the subsequent maize crop could be an efficient way to reduce N leaching while not compromising water and N requirements to maize.

Cover crop effect on maize yield

Maize grain yield reductions were observed in the barley cover crop treatment in 2007 (decrease ≈ 4 Mg ha^{-1}) and in a lesser extent in the barley and oilseed rape cover crop treatments in 2008 (decrease ≈ 1 Mg ha^{-1}). In all the other cases, the cover crop biomass incorporated into the soil and the reduced N fertilizer applied (250 kg N ha^{-1}) was sufficient to fulfill maize N requirements similarly to the control, supplied with an extra 50 kg N ha^{-1}. Therefore, winter rape, vetch and in the first year oilseed rape, proved to be efficient in reducing soil N content compared to the control and the associated N leaching risks, while maintaining maize crop yield with lower fertilizer N input.

The decrease of maize yield found after barley in both years and oilseed rape in 2008 were explained by a N deficiency of maize plants, as indicated by the lower SPAD values, the lower maize N uptake, and the lower end of season maize stalk nitrate test concentrations in these treatments compared to the control. The higher decrease of maize yield after the barley cover crop treatment in 2007 was related with a higher N deficiency.

N deficiency can occur if N release from organic sources is not synchronized with the N demand by the crop (Cavero et al., 1997; Magdoff, 1991). A timed N release is especially relevant in crops with determinate growth habit such as maize, especially when they have a high N demand in a short period of time (Salmerón et al., 2010). The maize N deficiency after the barley cover crop was probably due to the high C:N ratio of the barley biomass, that caused N immobilization (clearly shown in the 2007 N balance) and therefore a low availability of this N during the maize growing season. Incorporation of cover crops or other plant residues with high C:N ratio has been reported to decrease soil N inorganic and reduce N availability to maize (Starovoytov et al., 2010; Sainju et al., 2005; Baggs et al., 2000). Some works have clearly established that the incorporation of cover crop residues with C:N ratios above 25 result in N immobilization (Kaye and Hart, 1997; Ranells and Wagger, 1996). An earlier incorporation of the barley cover crop residue could have reduced the C:N ratio in the cover crop biomass. Moreover, the results suggest that a cereal-legume biculture could be an efficient combination to ensure a good establishment and obtain a cover crop residue with a higher N concentration (Sainju et al., 2005; Ranells and Wagger, 1997) and it would be interesting to study in our area. The maize yield reduction after the oilseed rape cover crop in 2008 could be explained by the low biomass produced and therefore the small amount of N mineralized from the cover crop as shown in the N balance. N immobilization is not likely to be the cause for the N deficiency in these treatment, as C:N ratio in this cover crop was below the proposed threshold for immobilization of 25 (Kuo and Jellum, 2000; Kaye and Hart, 1997; Ranells and Wagger, 1996). High N availability after vetch was clearly shown as N net mineralization during the maize crop occurred both years, which resulted in maize yield similar to the control.

Our results agree with previous works where maize yield after cover crops was greatly dependent on the quality of the cover crop residue (C:N ratio) incorporated into the soil (Starovoytov et al., 2010). High N availability after legume cover crops, and reduced N contents after cereal cover crops have been reported (Starovoytov et al., 2010; Baggs et al., 2000; Ranells and Wagger, 1996). High precipitations during winter and spring as well as irrigation management will likely affect the cover crop effect on soil N availability as compared to a control with bare soil during winter. Therefore, N recommendations to maize based merely on cover crop N content incorporated into the soil and/or based on soil N content after a cover crop will more likely fail to give optimum maize yields. Cover crop quality and climate and irrigation conditions should be taken into account, what can be difficult under field conditions.

N fertilizer recommendation tools that allow in season N fertilizer applications could be useful to adjust N fertilizer rates to maize after cover crops. SPAD measurements in maize leaves can indicate N deficiencies when compared with a well fertilized area (Varvel et al., 2007). SPAD values were able to detect maize N deficiencies early in the season both years which resulted in yield reduction both years. When the N deficiency was higher the SPAD values were lower at later maize stages (R1 and R5) and consequently the yield decrease was more important ($\approx$ 4 Mg ha^{-1}). This tool has previously shown to be useful to indicate N status in maize after cover crops (Miguez and Bollero, 2006) and in previous studies in the area (Salmerón et al., 2010). Therefore, the use of SPAD can be a valuable tool when using cover crops because of the uncertainty of N availability due the mineralization-immobilization processes of cover crops residue.

Maize stalk nitrate concentration at maize harvest is an end-of-season diagnostic test of N fertilizer management (Hooker et al., 1999; Blackmer et al., 1994; Binford et al., 1992). In this experiment the maize stalk nitrate was efficient detecting differences between treatments and was well related to maize yield. Thus, this tool was able to detect N deficiency in the barley treatment in 2007, with NO_3-N contents (35 mg kg^{-1}) much lower than the threshold of 250 mg kg^{-1} for N deficiency proposed by Binford et al. (1992). In the other treatments and years the stalk nitrate concentrations were within the range for sufficiency (300 to 1,800 mg kg^{-1} of NO_3^--N) to achieve maximum or near-maximum yield (Binford et al., 1992). In all cases, maize stalk nitrate concentrations were below 1,800 mg kg^{-1} of NO_3^--N which indicates that maize was not over fertilized.

5. CONCLUSIONS

Cover crops were able to produce biomass and N uptake in the high range of those reported in other conditions and proved to be a feasible practice under the Mediterranean irrigated semiarid conditions. Direct seeding allowed greater biomass production and N uptake in the first year, but not in the second year due to a poor establishment of the non-cereal cover crops.

Cover crop treatments reduced soil inorganic N in spring and at maize harvest, reducing the N leaching risk.

Maize yield after vetch, winter rape, and winter rape cover crops was as high as the control (bare soil) in one of the two years and slightly lower (-7%) in the other although N fertilizer applied was reduced by 50 kg N ha^{-1}. On the other hand, maize yield was reduced after barley cover crop by 1 to 4 Mg ha^{-1} (-6% and -25%, respectively) compared to the control because of maize N deficiency caused by low N availability due to insufficient N mineralization and/or lack of synchronization with maize N uptake.

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Capítulo 5

Applicability of the DSSAT-CENTURY models to simulate cover crop-maize rotations and nitrogen cycling in irrigated Mediterranean conditions.

Capítulo 5: Applicability of the DSSAT-CENTURY models to simulate cover crop-maize rotations and nitrogen cycling in irrigated Mediterranean conditions.

ABSTRACT

In the semiarid conditions of the Ebro river basin maize is grown under irrigation and can reach high yields (14 Mg ha^{-1}) but N leaching is a big concern. Cover crop growth during the winter time can reduce N leaching. A set of experimental data was used to calibrate and test the DSSAT-CENTURY model when cover crops are used in monoculture maize. The adapted EPIC soil temperature subroutine improved soil temperature predictions compared to DSSAT v. 4.5 soil temperature subroutine. DSSAT-CERES Maize was able to simulate averaged maize N content in the aboveground biomass of maize after the cover crops with RMSE below 55 kg N ha^{-1}. However, the model failed to simulate maize grain yield reductions of 10 to 20 % in maize after barley and winter rape apparently due to a low sensitivity of N deficiency to translate in reduced number of grains. N leaching reductions in maize after a cover crop as compared with maize after fallow were adequately simulated by the model (RMSE across all years and treatments = 7 kg N ha^{-1}. The use of a cereal cover crop in monoculture maize in La Violada Irrigation District would reduce N leaching loads in drainage by 50% at N fertilizer rates applied ranging from 250 to 350 kg N ha^{-1} with a mean decrease in yield of 0.7 Mg ha^{-1}. The benefits of using cover crops to reduce N leaching depending on the type of soil and the leaching fraction used to calculate the irrigation water applied was also studied.

Abbreviations:

DSSAT, Decision Support System for Agrotechnology Transfer; SOM, soil organic matter; SOC, soil organic carbon; RMSE, root mean square error.

1. INTRODUCTION

Maize is a crop with a high N demand, being recognized as one of the major diffuse contributors to N pollution of return flows from irrigated agriculture in semiarid Mediterranean conditions (Isidoro et al, 2006; Causape et al, 2004; Cavero et al, 2003; Diez et al, 1997) and other irrigated areas of the world (Klocke et al, 1999; Pratt, 1984). The use of cover crops can help to reduce N losses in maize (Salmerón et al, 2010; McCracken et al, 1994), but growing maize after a non-leguminous cover crop can result in yield reductions, especially when N fertilizer rates to maize are reduced (Salmerón et al, 2010; Miguez and Bollero, 2006; Vyn et al, 1999; Clark et al, 1997). A good estimation of cover crop N mineralization is therefore very important in order to predict maize N fertilizer needs in cover crop-maize rotation schemes and to avoid maize yield reductions and N leaching losses.

The use of models to simulate cover crop growth and the consequences of its decomposition in the subsequent maize crop can be a powerful tool for studying the ability of winter cover crops to reduce N leaching in different scenarios while minimizing yield reductions in maize. Once models are validated, they can be used to explore better crop management strategies (Royce et al., 2001; Ruiz-Nogueira et al, 2001; Boote et al, 1996; Kovacs et al, 1995).

DSSAT CERES-Maize model

The Decision Support System for Agrotechnology Transfer (DSSAT; Tsuji et al., 1994) is a comprehensive decision support system for assessing agricultural management options. This suite of models has been widely used and has proved to simulate accurately crop growth and yield in a wide range of weather and conditions. DSSAT incorporates the CERES-Maize submodel for the maize crop simulations. CERES-Maize is a relatively simple deterministic model that simulates maize development, growth and yield (Jones and Kiniry, 1986). This model calculates maize phenology, the rate of growth and the partitioning of biomass into the different growing organs on a daily basis. Under non-limiting conditions of water and N the simulated processes are affected only by the genotype and by environmental conditions (solar radiation, temperature), but the model can be used to simulate crops grown under water and N limiting conditions. CERES-Maize has been tested under a range of conditions for its correct simulation of maize grain yield (Kiniry et al, 1997; Carberry et al, 1989) and for water balance simulation capacity (Gabrielle et al, 1995, Kovacs et al, 1995). Model studies under a range of N availability to maize gave good predictions under rainfed conditions in Iowa (Paz et al, 1999), Minnesota (Pang et al, 1998), and Kenya (Keating et al, 1991). The model was also able to simulate mineralized N from green manure in Brazil (Bowen et al, 1993). However, limited information is available about the model use under N limiting conditions or with a wide range of amounts and quality of cover crop biomass. The need to adjust some model parameters for different conditions is known (López-Cedrón et al, 2008; López-Cedrón et al, 2005; du Toit et al, 2002; Castrignano et al., 1998; Carberry et al, 1989). Moreover, further testing and validation of the functions describing N cycling are required (Carberry et al, 1989).

The cover crop-maize rotation experiments we present here give a good opportunity to test the accuracy of the model to simulate the N mineralization of cover crops in irrigated Mediterranean conditions and the derived effect on maize grain yields and N leaching.

Soil Organic Matter models

The DSSAT crop simulation models includes a module for soil organic matter (SOM) simulation based on the PAPRAN module (Seligman and Van Keulen, 1981) adapted by Godwin and Jones (1991). However, some limitations for N mineralization were found for the PAPRAN module (Gijsman et al, 2002; Gabrielle and Kengni, 1996), mostly related to the fact that it only recognizes recently added residues and one kind of SOM pool. For this reason, the CENTURY soil organic matter module (Parton et al, 1994) was adapted and incorporated into the DSSAT (Gijsman et al 2002). The CENTURY model has previously proved to simulate accurately long term SOM dynamics (Kelly et al., 1997; Smith et al., 1997), but most of the studies deal with carbon mineralization processes and less with nitrogen. The detailed N simulation capability of the CENTURY model should be very relevant for simulating a cover crop – maize rotation with reduced N fertilization, where a significant portion of N available N for maize is coming from N mineralization of cover crops residues rather than from N fertilizer.

Soil temperature function in DSSAT

SOM and organic residue decomposition simulation is greatly affected by soil temperature (Stroo et al, 1989), so this variable needs to be accurately simulated for a good N mineralization estimation. The DSSAT soil temperature model is based on a simplified form of the EPIC soil temperature routine (Williams et al, 1989). In its simple form it does not take into account irrigation or precipitation events to compute daily soil temperature. A good prediction of soil temperature can be of greater importance under irrigated conditions in a semiarid climate, where irrigation applications can decrease temperature as compared to non-irrigated fields (Cavero et al, 2009). DSSAT has proved to simulate accurately soil water content under irrigated conditions and under water limiting conditions (Lopez-Cedrón et al, 2008). However, soil temperature simulation has not been tested under irrigated conditions.

The objectives of the present work are:

- To evaluate the accuracy of DSSAT-CERES Maize model to simulate maize yield and growth under the N limitation conditions of maize grown after cover crops with reduced N fertilization.
- To test the accuracy of the DSSAT-CENTURY model for predicting soil and cover crop mineralization, in terms of total maize N uptake, soil residual N at maize harvest and N leaching.
- To test the EPIC soil temperature model for simulating observed soil temperature in irrigated semiarid conditions in comparison with default DSSAT v.4.5 soil temperature subroutine.
- To use the model to predict N leaching and maize grain yield in maize-fallow and maize-non-legume cover crop rotations for a range of soil types, N fertilizer rates and drainage leaching fractions in an irrigated watershed.

2. MATERIALS AND METHODS

Experimental field data

Two experiments were conducted from 2006 to 2008 in the Centro de Investigación y Tecnología Agroalimentaria (CITA) experimental station, located in the Ebro river valley (0º49'W,41º44'N) in Zaragoza, Spain. Maize was rotated with winter cover crop in drainage lysimeters in Experiment 1, and in an experimental field located 1 km away in Experiment 2. The maize cultivar used was Pioneer PR34N43 (FAO 600 cycle). Detailed experiment descriptions are given in Salmerón et al (2010).

The drainage lysimeters of Experiment 1 were filled 10 years before the experiment started with a silt loam soil (23% sand, 51% silt and 26% clay) with a bulk density of 1.46 g cm^{-3}. It is a calcareous soil with a $CaCO_3$ equivalent of 326 g kg^{-1}, a pH of 8.2 (in water), average organic C content of 1.11% and organic N content of 0.11%. The soil in the field Experiment 2 is a clay loam (23% sand, 47% silt and 30% clay) classified as Typic Xerofluvent and with a bulk density of 1.40 g cm^{-3}. It is also a calcareous soil with a pH in water of 8.4 and an organic C content of 0.86% and 0.51% in the 0 - 0.3 and 0.3 - 1.2 m layers, respectively. Organic N content is 0.11 % and 0.09% in the 0 - 0.3 and 0.3 - 1.2 m layers, respectively.

The climate is Mediterranean semiarid with high solar radiation and mean annual maximum and minimum daily air temperatures of 20.9 and 8.5°C, respectively, yearly average precipitation of 322 mm and yearly average reference evapotranspiration (ETo) of 1100 mm. Meteorological data were measured with an automated weather station located in the experimental farm. Monthly averages during the experiments are presented in Table 1.

Table 1. Monthly values of meteorological data during 2007 and 2008. VPD is average vapor pressure deficit of the air.

Month	2007				2008			
	T max ºC	**T min ºC**	**Rain mm**	**VPD kPa**	**T max ºC**	**T min ºC**	**Rain mm**	**VPD kPa**
January	11	1	10	0.28	12	1	15	0.32
February	15	3	19	0.44	15	2	21	0.39
March	16	3	37	0.51	16	4	9	0.47
April	20	8	148	0.64	20	7	36	0.71
May	24	11	31	0.91	23	11	162	0.74
June	28	14	28	1.37	27	13	20	1.27
July	31	15	5	1.84	32	15	17	1.80
August	30	15	22	1.42	31	16	6	1.63
September	26	12	30	1.01	26	12	16	1.00
October	21	8	19	0.62	21	9	66	0.55
November	15	1	1	0.44	13	3	43	0.35
December	11	0	10	0.29	9	2	40	0.22

In both experiments, a two-year maize rotation with or without a winter cover crop was studied. In Experiment 1, four treatments were studied during the intercrop period of maize: bare soil and three different winter cover crops: winter barley (*Hordeum vulgare* L. *cv.*Hispanic), common vetch (*Vicia sativa* L. *cv.* Armantes), and winter rape (*Brassica rapa* L. *cv.* Perko*)*. In Experiment 2, a fourth cover crop was added: oilseed rape (*Brassica napus L. var. napus* cv. Madrigal), and two different cover crop sowing methods were tested after maize harvest: cover crops direct seeded, and cover crops sown after soil disking. The first method allowed 1-2 weeks earlier cover crop sowing times (Table 2). Maize residue was left in the field and incorporated into the soil prior to sowing of cover crops, or it was left on the surface in direct-seeded cover crops in experiment 2. Cover crops were grown during winter and incorporated into the soil to 20 cm depth at early spring, 2 weeks before maize sowing next year. Operation and planting dates are listed in Table 2.

Table 2. Dates of cover crop and maize sowing time, cover crop incorporation and maize harvest for the lysimeter experiment and for the field experiment.

Operation	Lysimeter experiment		Field experiment	
	2007	2008	2007	2008
Cover crop				
Sowing (DS)	-	-	3 Nov. 2006	30 Oct. 2007
Sowing (CT)	30 Oct. 2006	23 Oct. 2007	15 Nov 2006	7 Nov. 2007
Incorporation	19 Mar 2007	12 Mar 2008	12 Apr. 2007	7 Apr. 2008
Maize				
Sowing	24 Apr. 2007	15 Apr. 2008	8 May 2007	25 Apr. 2008
Harvest	9 Oct. 2007	9 Oct. 2008	23 Oct. 2007	24 Oct. 2008

DS: cover crop direct seeded after maize harvest
CT: cover crop seeded after conventional tillage operations

Maize was fertilized with 300 kg N ha^{-1} in the bare soil (fallow) treatment, and N fertilization was reduced when maize was grown after cover crops to give some credit to cover crop N mineralization. In Experiment 1, N fertilization was reduced according to the N content in the aboveground biomass of each cover crop as shown in Table 3. In Experiment 2, maize after cover crops was fertilized with 250 kg N ha^{-1}. N fertilizer was applied in 3 split applications, one third at preplant and two sidedress applications at maize V6 and V12 stages.

Table 3. Nitrogen (N) applied as green manure (cover crops incorporated) and N fertilizer to the maize crop in the different treatments of the lysimeter experiment (Experiment 1) in 2007 and 2008.

Treatment	N green manure	N fertilizer	Total N supplied
	---------------------------- kg N ha^{-1} ----------------------------		
		2007	
Control	-	300	300
Barley	172	154	326
Winter Rape	139	152	291
Vetch	47	266	313
		2008	
Control	-	300	300
Barley	141	159	300
Winter Rape	131	166	297

Maize was irrigated using a dense drip irrigation system that simulated flood irrigation in Experiment 1. Maize was sprinkler irrigated in Experiment 2. Irrigation requirements were calculated from the reference evapotranspiration (estimated with the FAO Penman-Monteith equation) and the crop coefficients, according to the FAO procedures (Allen et al., 1998) and considering a leaching fraction of 25% in the lysimeters and 15% in the field experiment.

Drainage from the lysimeters was collected by natural drainage in 50 L tanks set in an underground room. Drainage volume was measured on a weekly basis, and a sample of 100 mL was collected from each lysimeter. The NO_3-N concentration was determined colorimetrically with a continuous flow analyzer (AA3, Bran+Luebbe, Norderstedt, Germany).

In both experiments soil samples were taken each year after maize harvest and before cover crops were ploughed into the soil. Soil was sampled with a manual auger to 1.20 m and samples for each 0.3 m depth increment. Before the cover crops were incorporated into the soil, cover crop biomass was measured by harvesting 1 m^2 in each plot. This was dried at 65ºC, weighed and ground before total N and C were determined by combustion (TruSpec CN, LECO, St. Joseph, MI, USA). Cover crop biomass and N content are summarized in Table 4 for the two experiments. Maize was hand-harvested in October 2006, 2007 and 2008 to assess yield and yield components. Two subsamples were dried at 65ºC, weighed and ground prior to measuring total N and C (TruSpec CN, LECO, St. Joseph, MI, USA). Further details of the lysimter experiment management and measurements are given in Salmerón et al. (2010).

Table 4. Observed and DSSAT simulated cover crop biomass and N content in spring 2007 and 2008 in the lysimeter and field experiments. Values between brackets for the observed data represent standard error.

	2007			
	Biomass (kg ha^{-1})		N content (kg ha^{-1})	
	Observed	Simulated	Observed	Simulated
Lysimeter experiment				
Barley	6266 (661)	6344	152 (25)	113
Winter rape	4923 (662)	4989	126 (30)	110
Vetch	1117 (172)	1171	43 (6)	42
Field experiment				
Barley	4116 (586)	4114	70 (11)	69
Oilseed rape	1609 (395)	1767	46 (11)	46
Winter rape	714 (103)	778	18 (8)	17
Vetch	1501 (193)	1431	43 (7)	49
Barley DS	6993 (760)	7035	116 (28)	111
Oilseed rape DS	2315 (344)	2371	77 (16)	69
Winter rape DS	2416 (1010)	2418	87 (51)	71
Vetch DS	2956 (349)	2999	102 (14)	92

DS: cover crop direct seeded after maize harvest
CT: cover crop seeded after conventional tillage operations

Table 4 (continuation). Observed and DSSAT simulated cover crop biomass and N content in spring 2007 and 2008 in the lysimeter and field experiments. Values between brackets for the observed data represent standard error.

	2008			
	Biomass (kg ha^{-1})		N content (kg ha^{-1})	
	Observed	Simulated	Observed	Simulated
Lysimeter experiment				
Barley	6323 (575)	6402	127 (24)	106
Winter rape	4746 (806)	4963	119 (23)	99
Vetch	-		-	
Field experiment				
Barley	2187 (520)	2287	24 (7)	23
Oilseed rape	564 (113)	669	17 (3)	11
Winter rape	1963 (133)	1994	45 (4)	41
Vetch	1542 (236)	1556	56 (9)	52
Barley DS	3148 (502)	3062	45 (14)	46
Oilseed rape DS	1281 (123)	1341	38 (7)	30
Winter rape DS	823 (238)	858	22 (6)	17
Vetch DS	425 (338)	559	42 (5)	21

DS: cover crop direct seeded after maize harvest
CT: cover crop seeded after conventional tillage operations

DSSAT CERES-Maize Crop Model Calibration

General

DSSAT allows to use different equations to compute daily potential evapotranspiration. The method of Penman-Montieth-FAO56 (Allen et al., 1998) was used for the simulations, as it has proven to give better water balance predictions under water limiting conditions in northwest Spain (López-Cedrón et al, 2008). This method requires daily data of solar radiation, minimum and maximum temperatures, relative humidity and wind speed, which were obtained from a nearby weather station.

Light extinction coefficient (KCAN) in the ecotype file is set by default to 0.85 in DSSAT V4.5. This value was too high according to literature reviews on maize that show a range from 0.44 to 0.63 (Childs et al, 1977; Kang et al, 2003; Flenet et al, 1996). A value of 0.5 for KCAN improved DSSAT model simulations in NW Spain (López-Cedrón et al, 2008) and is similar to that measured under our growing conditions (Cavero et al, 2000), so a value of 0.50 was used in the simulations.

Radiation use efficiency (RUE) is known to decrease with increasing vapor pressure deficit (VPD). Stockle and Kiniry (1990) found that the increase of VPD reduces RUE in maize following the equations:

$$\text{If VPD} < 1\text{kPa, RUE} = 3.90 \text{ g MJ}^{-1} \quad (1)$$

$$\text{If VPD} \geq 1\text{kPa, RUE} = (4.55 - 0.65 \times \text{VPD}) \text{ g MJ}^{-1} \quad (2)$$

In our location, high VPD often occurs during the maize growing season, with daily values that can reach 3 kPa in July and August (Cavero et al, 2009). This is not taken into account in DSSAT V4.5, where RUE in CERES-Maize has a fixed value equal to 4.2 g MJ^{-1}, and therefore, RUE and the derived biomass and grain yield may be overestimated in locations with high VPD values. To avoid this, an average VPD value for the maize growing season from emergence to physiological maturity was calculated for each year and experiment following the equations proposed by Stockle and Kiniry (1990). Then, the reduced RUE as a function of VPD was calculated for each year and experiment according to equations 1 and 2 and used in the model. Average RUE obtained across all years and experiment was 3.65 g MJ^{-1}.

Crop Coefficients Calibration

CERES-Maize requires the estimation of 6 cultivar dependent coefficients. Measured data for the bare soil treatment from the two experiments and for the two years was used to derive the values of the 6 coefficients because this treatment did not have limitations of water and nitrogen (Salmerón et al, 2010). Model runs with DSSAT-CERES-Maize v4.5 were performed with the Nitrogen and Water simulations options turned “on”. The P1 (Growing degree days to flowering) and P2 (Delay in development with photoperiod above 12.5h, expressed as days) coefficients were adjusted to predict the observed day of flowering, and P5 (Growing degree days to maturity) was adjusted for the day of maturity. Grain yield was adjusted by setting G3 (Potential kernel growth rate) with the observed weight per kernel and G2 (Potential kernel number per plant) was adjusted versus the number of kernels per unit land area. PHINT (Phylochron interval) was the interval in thermal time (degree days) between successive leaf tip appearances. The derived cultivar coefficients were: 243, 0.6, 837, 959, 6.77 and 51.2 for P1, P2, P5, G2, G3 and PHINT, respectively. Average observed and simulated biomass, grain yield, harvest index, kernel weight and number of kernels per unit land area for the different experiments are shown in Table 5.

Table 5. Observed and DSSAT simulated values and comparison statistics in the bare soil treatment for maize phenology and growth with the new EPIC soil temperature model (n=6).

	Observed	Simulated		
Variable Name	**Mean**	**Mean**	**RMSE**	**d-Stat.**
Anthesis day (DAP)	83	82	1.5	0.96
Maturity day (DAP)	140	139	1.7	0.52
Tops weight (kg ha^{-1})	26884	25970	1165	0.90
Grain Yield (kg ha^{-1})	13620	13678	441	0.93
Harvest index	0.53	0.52	0.03	0.24
Kernel weight (g/unit)	0.290	0.294	0.02	0.52
Number kernels/m^2	4707	4666	329	0.71
Tops N kg ha^{-1}	289	273	41	0.19
Grain N kg ha^{-1}	192	220	32	0.42
% N in grain	1.41	1.74	0.36	0.24

DAP: days after planting.
RMSE: Root mean square error.
d-Stat.: d- Statistic or Index of agreement (Willmott, 1982).

Soil characteristics and soil profile calibration

A soil profile for each experiment was created in DSSAT. The pedotransfer function calculates three water holding parameters based on soil texture and soil organic carbon content: drained upper limit (DUL), lower limit or water content at wilting point (LL) and water content at saturation (SAT). The estimated DUL values were recalibrated (reduced) in the lysimeter soil for a better fit with the measured gravimetric water. Hydraulic conductivity was reduced in the bottom layer of the lysimeter soil profile for simulating drainage lysimeter conditions (open air bottom with no soil tension) and reducing the rate of drainage over time. The soil profile parameters used are shown in Table 6.

In order to achieve the observed aboveground biomass in the bare soil treatment, the soil fertility factor was set to 1.00 in the lysimeter experiment, and to 0.90 in the field experiment. A reason for this lower soil fertility factor in the field experiment could be a higher soil compaction of this soil due to machinery and a long term maize rotation (since 2005).

Table 6. Characteristics of the soils used in the simulations. Water content at wilting point (LL), drained soil water limit (DUL), and water content at saturation (SAT). Soil rooting preferent function used by DSSAT model (SRGF) and hydraulic conductivity (Ksat).

	Lysimeter experiment					**Field experiment**				
Soil Layer	**LL**	**DUL**	**SAT**	**SRGF**	**Ksat**	**LL**	**DUL**	**SAT**	**SRGF**	**Ksat**
m	----------- % vol. -----------			0-1	cm h^{-1}	----------- % vol. ----------			0-1	cm h^{-1}
0 - 0.05	18.9	35.8	53.2	1.00	0.5	19.0	35.0	49.2	1.00	0.5
0.05 - 0.15	18.9	35.8	53.2	1.00	0.5	19.0	35.0	49.2	1.00	0.5
0.15 - 0.30	20.0	35.8	53.2	1.00	0.5	19.0	35.0	49.2	1.00	0.5
0.30 - 0.60	19.7	35.2	52.8	0.41	0.4	19.1	35.1	49.7	0.41	0.4
0.60 - 0.90	19.4	34.5	52.5	0.22	0.4	20.1	36.3	49.2	0.22	0.4
0.90 - 1.20	19.3	34.7	52.5	0.12	0.15	18.9	34.9	49.6	0.12	0.15

CENTURY model estimation of soil organic carbon (SOC) pools

The total soil organic matter is divided in the model into two fresh organic matter (FOM) pools and three soil humic organic matter pools (SOM). The two FOM pools are the metabolic or easily decomposable litter (e.g. proteins, sugars) and the structural or recalcitrant fresh residue (e.g. lignin, cell walls). The three SOM pools are: microbial or active material (SOM1), recalcitrant and stabilized microbial material (SOM2) and the largely inert stabilized microbial material (SOM3). The FOM decomposes rapidly on the order of days, and the three SOM pools decompose in the order of days, years and hundreds of years, respectively.

To initialize the soil organic C, the CENTURY model subtracts the supplied FOM (from previous crop residue) from the total measured organic C to obtain the humic SOM. The value of SOM3 can then be estimated by the model or given as an input, and the model assumes the fractions of SOM1 and SOM2 to be 5% and 95% of the remaining amount of SOM, respectively (Porter et al, 2010). Therefore, the model needs SOM3 as an input or this can be estimated by the model based on soil texture and management history. In our work the value of SOM3 was estimated. Because the SOC some years before the start of the experiment is not known for long term simulations of OC, the passive SOM pool was estimated using the iterative procedure described by Basso et al (2011). Before starting simulations with DSSAT, a long term 10,000 year simulation with the CENTURY model (Parton et al, 1994) of a tree-grass system in a similar soil in the same climate conditions was used as start values of total and passive soil organic carbon (Alvaro-Fuentes et al, 2009). Then, a 60 year simulation was conducted with

DSSAT of an approximate cropping history and repeated iteratively until the final SOC was similar to the one at the start of the experiment (Figure 1 and 2). The approximate cropping history simulated for the 60 years consisted of a 35-year simulation with DSSAT CERES-Barley to simulate a winter cereal crop without irrigation and with no N fertilizer. After this, a 25-year period of an irrigated maize crop (890 mm yr^{-1} applied) with 240 kg N ha^{-1} yr^{-1} applied was simulated. Crop residue left in the field was set to 15% for barley and maize, trying to simulate similar field conditions. The SOM pools over the 60 last years of simulation are shown for each experiment in Figure 1 and 2. The obtained final fraction of SOM3/Total SOC was then used to initialize the cover crop-maize simulations using the CENTURY model subroutine in DSSAT v 4.5.

Soil temperature model

An adapted soil temperature subroutine from EPIC (described in Potter and Williams, 1994) was incorporated to DSSAT and compared to the current default version (a simplification of the EPIC version). Small modifications were made to the EPIC soil temperature subroutine described by Potter and Williams (1994) when adapting to DSSAT: (i) Irrigation events were taken into account as precipitation and computed as a wet day for temperature simulations, (ii) number of wet or dry days in a month was computed using the 30 days prior to the day of simulation when available instead of number of wet/dry days in a natural month, and (iii) the LAG parameter (coefficient ranging from 0 to 1 that allows weighting of yesterday's temperature with the current day's soil temperature estimate) was set to a fixed value of 0.5. Three data sets of measured soil temperature in an irrigated maize field from 2004-05, 2006-07 and 2009-10 maize growing seasons were used to compare the DSSAT v 4.5 soil temperature subroutine with the adapted EPIC soil temperature subroutine. Soil temperature was measured at 2 cm depth in 2005 and at 5 cm depth in 2007 and 2010 with thermistors probes (Model 107, Campbell Scientific, Shepshed, UK).

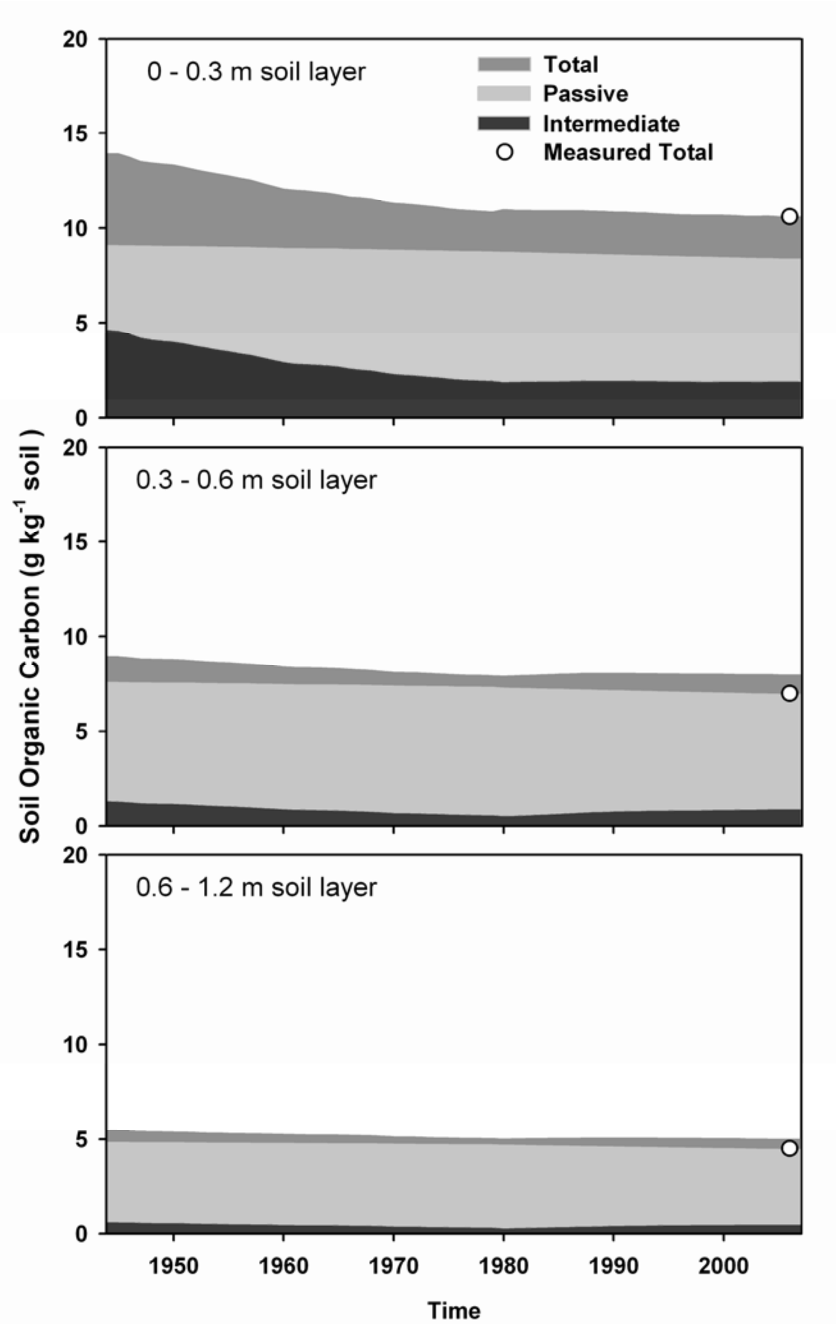

Figure 1. Simulated total, passive and intermediate soil organic carbon during the 60 years prior to the start of the field experiment. Data presented for the different soil layers.

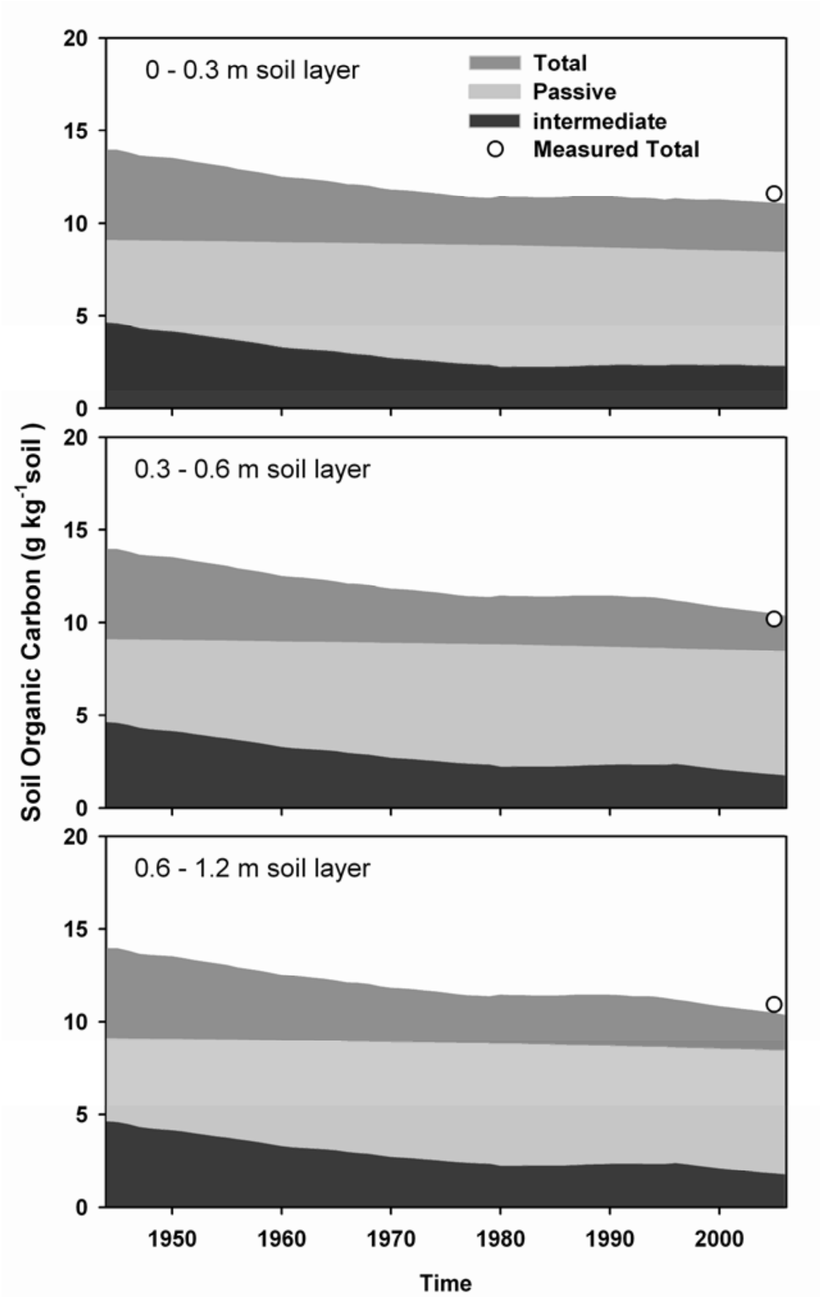

Figure 2. Simulated total, passive and intermediate soil organic carbon during the 60 years prior to the start of the experiment in the lysimeter. Data presented from the 0 to 0.3 m soil layer during the first 50 years, and from the soil profile in the lysimeter in the last 10 years.

DSSAT Model testing with cover crops

Cover crops – Maize simulations

After calibrating the DSSAT CERES-Maize model with the bare soil treatment, the model was tested using the rest of treatments where maize was grown in rotation with different cover crops. The Sequence application in DSSAT was used to simulate the cover crop growth and incorporation before simulating the maize crop. Cover crops were simulated with the crop model CERES-Barley for the non-legume cover crops, and with CROPGRO-Faba bean for vetch. Barley and faba bean genetic coefficients and sowing density were modified to obtain the observed cover crop biomass and N uptake at the moment before being incorporated into the soil (Table 4). Simulated cover crop biomass and N uptake was close to the observed averages and within standard error ranges in most cases (Table 4). The only simulated value that has a relevant discrepancy with the observed mean was the N content of barley in the lysimeter experiment in 2007 (simulated value was 39 kg N ha^{-1} below the observed). In some other cases the N content of the cover crops was outside the standard error limits but the total amount of N was too low to be relevant (17 – 42 kg ha^{-1}).

To simulate cover crop incorporation into the soil before maize planting, cover crop harvest was set to 0% takeoff of harvest product and byproduct so that the model would consider them 100% incorporated into the soil after a tillage operation simulation.

Different cover crop scenarios.

Once the model was proven to accurately simulate N leaching and maize grain yield when cover crops were grown during the winter period, different scenarios were simulated with the model. The soil, weather and crop management conditions used for the simulations were those of the La Violada irrigated watershed (5282 ha), located in the Ebro River basin in northeastern Spain (Isidoro et al, 2006). The N management and N loss in this watershed has been studied for decades (Isidoro et al, 2006; Bellot et al, 1989), which provides a good testing for the model. Simulations were made over a series of 14 years or 13 maize growing seasons, with weather data for the La Violada watershed.

The simulations considered that maize was irrigated according to the FAO procedures (Allen et al, 1998). Maize irrigation requirements were calculated weekly and averaged across the 13 maize growing seasons studied. An 85 % irrigation efficiency was considered for the irrigation requirements calculations. A leaching fraction (water applied in excess of irrigation requirement) of 0.1 was considered to ensure there is not salt accumulation and make similar conditions to the ones in the watershed. Thus, the average annual irrigation requirement calculated was 800 mm and was used across all years for simplicity and because the Seasonal application does not allow different irrigation applications each year. Irrigation events were applied twice per week.

Maize was fertilized with 300 kg N ha^{-1}, a value similar to the reported N uptake of the crop (Salmerón et al, 2010), and lower than the N rate used by growers in this wathershed, that ranged from 398 to 452 (Isidoro et al, 2006). N fertilizer was applied in three equal N applications at pre-plant and two sidedress N applications close to 6 and 12 leaves stage. The three main soils in the watershed were considered for the simulations (Table 7). Soil A has the higher water retention capacity, whereas soil B and C have lower water retention capacity, lower depth, and a higher coarse fraction.

The first scenario studied was the soil cover during the maize winter period, that was set to either bare soil/fallow or to a non-legume cover crop. The second scenario studied different N fertilizer rates applied to maize (250, 300 and 350 kg N ha^{-1}) in the soil type A (Table 7). The third scenario studied the three different soils found in the watershed (A, B and C). The fourth scenario studied the use of different irrigation leaching fractions in the soil type A: 0, 0.05, 0.1 and 0.15, that correspond to 720, 758, 800 and 848 mm of water, respectively.

Simulations were conducted as a 14 year rotation with the SEQUENCE application in DSSAT. Simulations started in October 1994 after maize harvest. The cover crop was simulated with CERES-Barley and was incorporated into the soil two weeks before maize sowing. Soil inorganic N content at the start of the simulations in October was set to 10 mg kg^{-1} soil in all the soil profile for both the cover crop and fallow treatments.

Table 7. Characteristics of the soils in La Violada Irrigation District used in the simulations. Water content at wilting point (SLLL), drained soil water limit (SDUL), and water content at saturation (SAT).

Soil depth	Coarse fragment (%)	Silt (%)	Clay (%)	Bulk density (Mg m^{-3})	FC (SDUL) (m/m)	WP (SLLL) (m/m)	Organic C (%)
				Soil A			
0-0.30	6	62.8	30.4	1.3	0.308	0.189	1.03
0.30-0.60	6	56.6	35.5	1.3	0.308	0.189	0.90
0.60-0.90	6	63.3	28.8	1.3	0.308	0.189	0.68
0.90-1.20	6	63.3	28.8	1.3	0.308	0.189	0.68
				Soil B			
0-0.30	28	57.5	32.5	1.3	0.242	0.149	0.94
0.30-0.60	28	56.1	31	1.3	0.242	0.149	0.46
0.60-0.90	28	56.7	31.4	1.3	0.242	0.149	0.37
0.90-1.10	28	56.7	31.4	1.3	0.242	0.149	0.37
				Soil C			
0-0.30	30	59.9	27.8	1.3	0.144	0.088	1.27
0.30-0.60	30	54.2	32.5	1.3	0.144	0.088	1.05
0.60-0.825	30	56.1	33.2	1.3	0.144	0.088	0.97

Statistical analysis

In order to assess the performance of the model, the following criteria were used:

(i) The root mean square error (RMSE) between observed and simulated values was computed as:

$$RMSE = \left[N^{-1} \sum_{i=1}^{n} (P_i - O_i)^2 \right]^{0.5} \tag{3}$$

where N is the number of observed values, O_i and P_i are observed and predicted values for the i^{th} data pair. The model fit is better as RMSE values are closer to 0.

(ii) Index of agreement (d; Willmott, 1982), that is an aggregate overall indicator that is of more value than R^2. The model fit improves as d-index approaches unity. The d-index was computed as follows:

$$d = \frac{\sum_{i=1}^{n}(P_i - O_i)^2}{\sum_{i=1}^{n}(|P'_i| - |O'_i|)^2} \tag{4}$$

where n is the number of observed values, Oi and Pi are observed and predicted values for the i^{th} data pair, $P'_i = P_i - O_{av}$ (average of the observed data) and $O'_i = O_i - O_{av}$.

(iii) Regression analysis with and without forced zero intercept with the SAS software.

3. RESULTS

DSSAT CERES-Maize Crop Model Calibration

Soil temperature simulations

Soil temperature simulations with the original subroutine in DSSAT v.4.5 and with the adapted EPIC soil temperature subroutine are presented in Figure 3 for three different periods in the field experiment. Measured soil temperature at 2 cm depth during the 2005 maize growing season averaged 22.5 ºC, whereas that simulated by the original subroutine in DSSAT v.4.5 at 5 cm depth averaged 29.4 ºC during the same period. With the adapted EPIC soil temperature subroutine simulated soil temperature averaged 24.2 ºC. The RMSE of the simulated and observed soil temperature improved from 7.2 to 2.7 ºC when using the adapted EPIC soil temperature subroutine instead of the original subroutine in DSSAT v.4.5. Similarly, during the maize growing season in 2010, measured soil temperature at 5 cm depth averaged 21.1ºC whereas simulated soil temperature for the same period averaged 29.3 and 24.2 ºC with the original subroutine in DSSAT v.4.5 and with the adapted EPIC soil temperature subroutine, respectively. The RMSE improved from 8.6 to 3.9 ºC when using the EPIC soil temperature subroutine. Finally, during the cover crop growth period in 2007, measured soil temperature at 5 cm depth averaged 5.9 ºC, whereas simulated soil temperature with the original subroutine in DSSAT v.4.5. and with the adapted EPIC soil temperature subroutine were 7.3 and 6.7 ºC, respectively. The RMSE was reduced from 3.4 ºC with the original subroutine in DSSAT v.4.5 to 2.9 ºC with the adapted EPIC soil temperature subroutine.

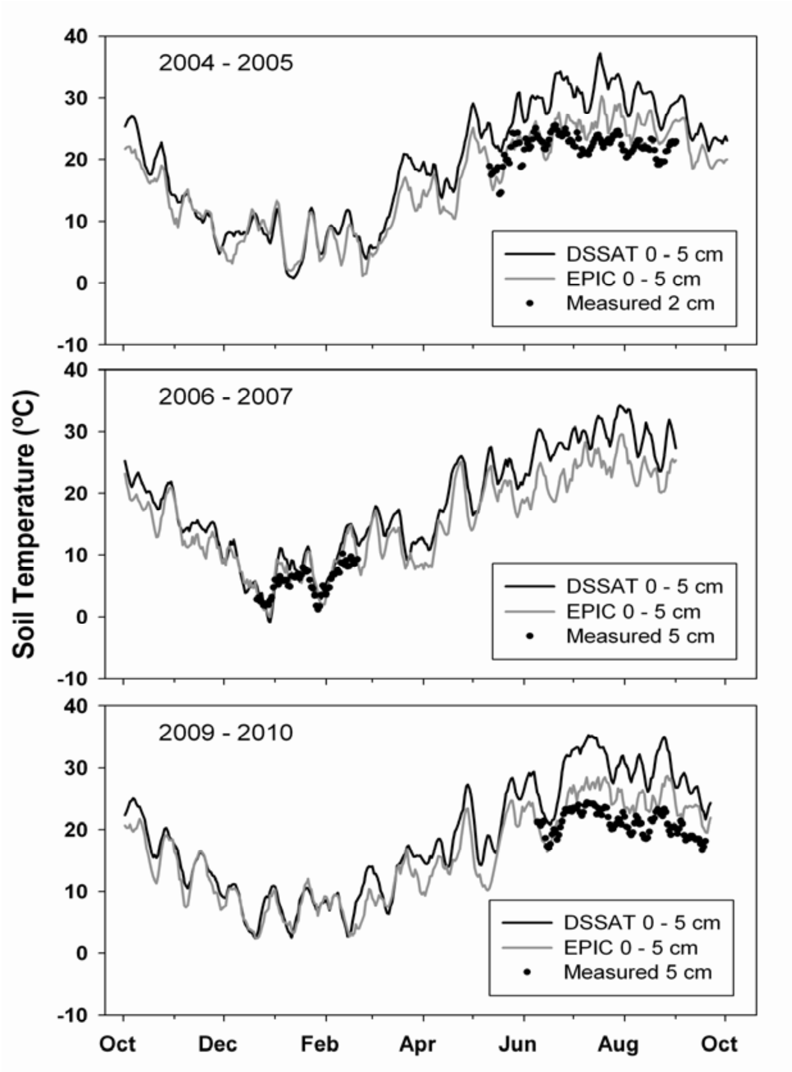

Figure 3. Comparison of measured soil temperature at 2 cm depth (2005) and at 5 cm depth (2007 and 2010) during three periods in the 2004-2005, 2006-2007 and 2009-2010 maize growing seasons and simulated soil temperature with DSSAT using either the DSSAT soil temperature subroutine or the EPIC soil temperature subroutine.

According to these results all the following simulations were done using the adapted EPIC soil temperature subroutine.

DSSAT Model testing with cover crops

Soil water and N dynamics.

Simulated soil water content after the cover crops was 27 % higher than the observed data in the upper soil layer (0 to 0.3 m), but only 4 to 15 % higher than the observed in the deeper layers (Figure 4). RMSE ranged from 0.017 to 0.030 m^3m^{-3} in all the soil layers. At maize harvest, soil water content was 14 % higher in the upper soil layer, but the prediction of soil water content was correct for the deeper layers (Figure 4), with RMSE below 0.016 m^3m^{-3} in all the soil layers. The slight over-estimation of soil water content after the cover crops can be due to an underestimation of simulated evapotranspiration. However, a similar result was found in the bare soil treatment, where no cover crop was grown.

Cumulative drainage water measured at the lysimeter experiment was in general within the standard error of measured values for both the bare soil treatment and the cover crops treatments (Figure 5). Pooling data from different soil cover treatments and years, total cumulative drainage was only 12% higher in the simulated values, with a RMSE of 60 mm.

Soil inorganic N after the period of cover crop growth was underpredicted in the 0 to 0.3 m soil layer, but in deeper layers simulated values were closer to the observed values (Figure 6). The RMSE of soil inorganic N after the cover crops ranged only from 1.97 to 3.42 mg kg^{-1}. Values of soil inorganic N in spring (after the cover crops) in the control treatment reflect the balance between mineralization and leaching during winter time, that seems to be correctly predicted. There was a high variation in soil inorganic N content, as often found in soil measurements due to soil variability.

At maize harvest, the model underestimated the soil inorganic N content in all soil layers (Figure 6). Simulated soil inorganic N in all the soil profile (0 to 1.2 m) at harvest ranged between 10 to 100 kg N ha^{-1}, whereas measured soil inorganic N content ranged from 50 to 220 kg N ha^{-1}. This underpredicton of the model soil inorganic N at maize harvest could be due to several factors that affect soil N content. One hypothesis is that the model overestimates the maize N uptake. Some other factors such as soil nitrate adsorption processes (Bowen et al, 1993) or preferential flows of water can greatly affect soil N content.

The N leaching measured in the drainage lysimeters is compared with the simulated N leaching in Figure 7. In the bare soil treatment the simulated N leached was higher than the observed in 2007, but was predicted with accuracy in 2008. Pooling data from the different soil cover treatments and years, the slope of simulated versus observed N leaching was 1.5 (R^2 = 0.82, P< 0.0001), which indicates an overestimation of N leaching by 50%. This large overestimation in relative figures was low in absolute figures. Thus, the decrease in N leached in the cover crop treatments was simulated by the model, and the RMSE between observed and simulated values across all treatments was only of 7.2 kg N ha^{-1}.

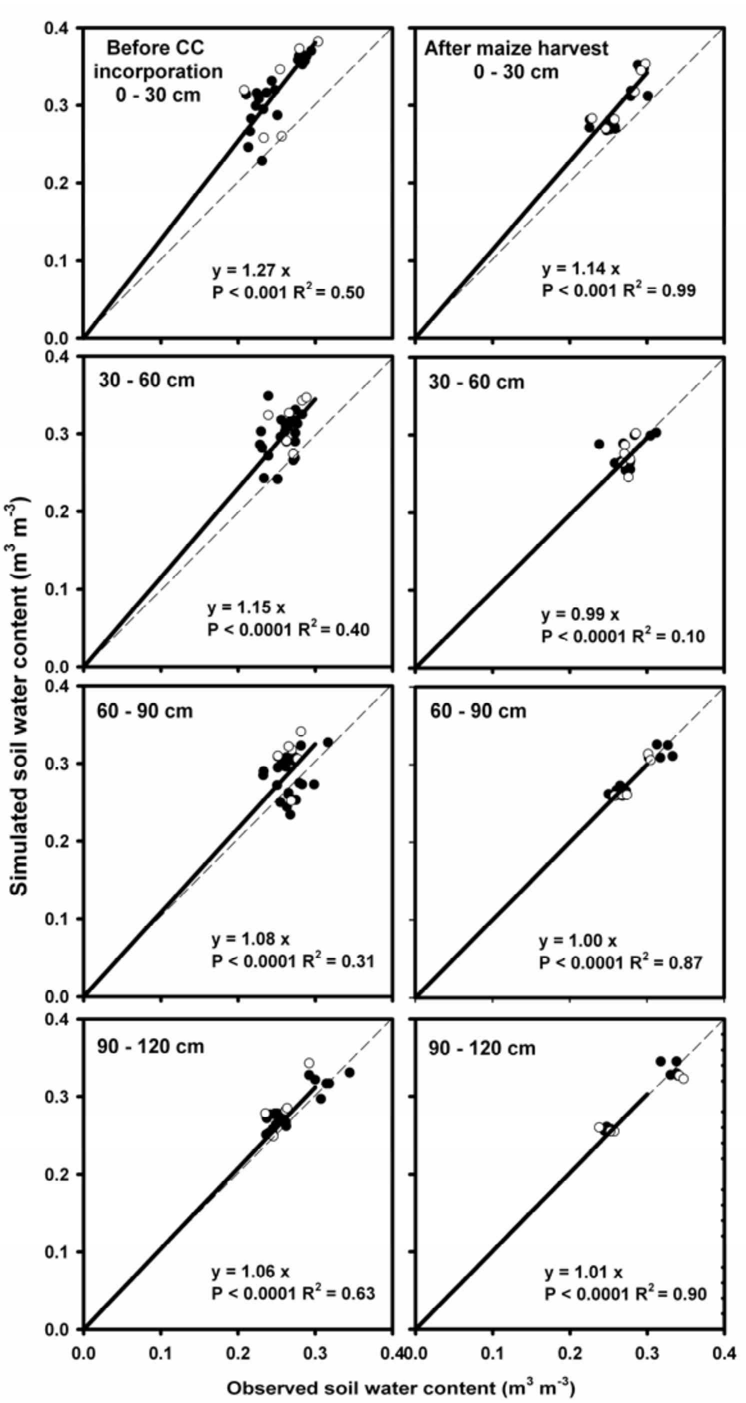

Figure 4. Observed and simulated soil water content in the 0 to 1.2 m soil profile before the CC incorporation (left) and at maize harvest (right). Open symbols represent maize alter fallow (○). Closed symbols represent maize after a cover crop (●).

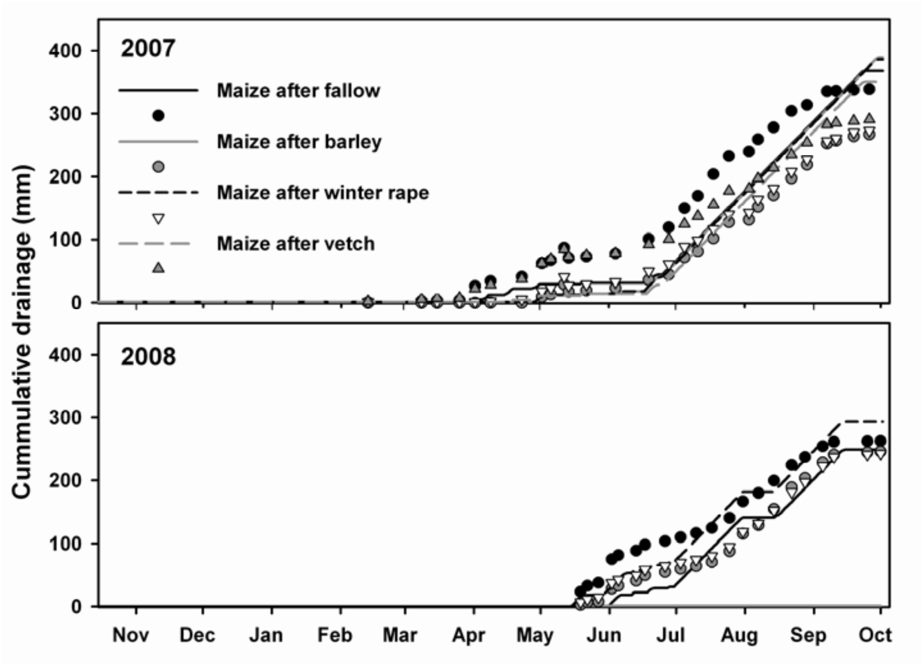

Figure 5. Cumulative drainage water measured in the lysimeters (symbols) and simulated (lines).

Maize yield and growth

The model correctly simulated maize grain yield of the vetch and oilseed rape treatments, with RMSE of 320 and 577 kg ha^{-1}, respectively (Table 8). In the case of maize after barley and after winter rape the grain yield was overestimated by 19 and 10 %, respectively (≈ 2 and 1 t ha^{-1}). Similar results were found for total aboveground biomass simulation. The number of maize grains per m^2 was correctly predicted in maize after vetch and oilseed rape cover crops, but overestimated by 12 and 6 % in the case of maize after barley and winter rape, respectively. Unit maize grain weight was correctly simulated in all cases except in maize after barley, where it was overestimated by 6 %.

The model correctly simulated the average N uptake of maize plants in all the cover crops treatments except in the barley treatment that was overestimated by 8 %. Grain N

Table 8. Mean simulated and observed maize grain yield, total aboveground biomass, number of grains per m^2 and unit grain weight, total plant and grain N content, plant and grain N concentration (%). The simulations were done with the adapted EPIC soil temperature routine. Data averaged per treatment across the two years and experiments. Root mean square error (RMSE) and Index of agreement (d-Stat.).

	Grain yield				**Aboveground biomass**			
CC treatment	**Obs.**	**Sim.**	**RMSE**	**d-Stat**	**Obs.**	**Sim.**	**RMSE**	**d-Stat**
	------------- kg ha^{-1} ------------				**-------------- kg ha^{-1} --------------**			
Control (n=6)	13620	13678	441	0.93	26884	25970	1165	0.90
Barley (n=6)	11393	13563	2576	0.31	23017	25916	3800	0.30
Oilseed rape (n=4)	12595	13133	577	0.86	25391	26232	1407	0.83
Winter rape (n=6)	12384	13582	1625	0.33	24165	26041	2315	0.63
Vetch (n=5)	13625	13461	320	0.97	25784	26573	1658	0.85
	Number of grains per m^{-2}				**Unit grain weight**			
	-------------- nº m^{-2} ------------				**------------------ g ------------------**			
Control (n=6)	4707	4666	329	0.71	0.2900	0.2945	0.0191	0.52
Barley (n=6)	4150	4655	545	0.66	0.2747	0.2929	0.0372	0.15
Oilseed rape (n=4)	4230	4367	227	0.13	0.2993	0.3013	0.0129	0.86
Winter rape (n=6)	4407	4662	439	0.52	0.2815	0.2929	0.0235	0.68
Vetch (n=5)	4486	4589	239	0.85	0.3056	0.2957	0.0198	0.50

Table 8 (continuation). Mean simulated and observed maize grain yield, total aboveground biomass, number of grains per m^2 and unit grain weight, total plant and grain N content, plant and grain N concentration (%). The simulations were done with the adapted EPIC soil temperature routine. Data averaged per treatment across the two years and experiments. Root mean square error (RMSE) and

	Total aboveground N				**Grain N**			
CC treatment	**Obs.**	**Sim.**	**RMSE**	**d-Stat**	**Obs.**	**Sim.**	**RMSE**	**d-Stat**
	------------ kg N ha^{-1} -----------				**------------ kg N ha^{-1} -------------**			
Control (n=6)	289	273	41	0.19	192	220	32	0.42
Barley (n=6)	216	234	55	0.13	145	194	59	0.28
Oilseed rape (n=4)	274	268	23	0.15	182	213	35	0.11
Winter rape (n=6)	236	244	35	0.63	163	201	45	0.39
Vetch (n=5)	283	277	32	0.52	192	221	30	0.56
	% N in the plant (stem + leaves)				**% N in the grain**			
	--------------- % ----------------				**------------------ % ------------------**			
Control (n=6)	0.70	0.51	0.24	0.32	1.41	1.74	0.36	0.24
Barley (n=6)	0.61	0.37	0.25	0.37	1.27	1.43	0.26	0.34
Oilseed rape (n=4)	0.73	0.48	0.25	0.32	1.45	1.67	0.35	0.45
Winter rape (n=6)	0.63	0.53	0.12	0.21	1.31	1.57	0.27	0.43
Vetch (n=5)	0.74	0.45	0.31	0.24	1.41	1.50	1.15	0.19

Index of agreement (d-Stat.).

mass was overpredicted in all treatments by 26 to 47 kg N ha^{-1} except in maize after vetch. The model underpredicted N concentration in the stems+leaves portion (average of 0.47 %) compared to the observed data (average of 0.68 %). On the other hand, the N concentration in the grain was overpredicted compared to the observed data.

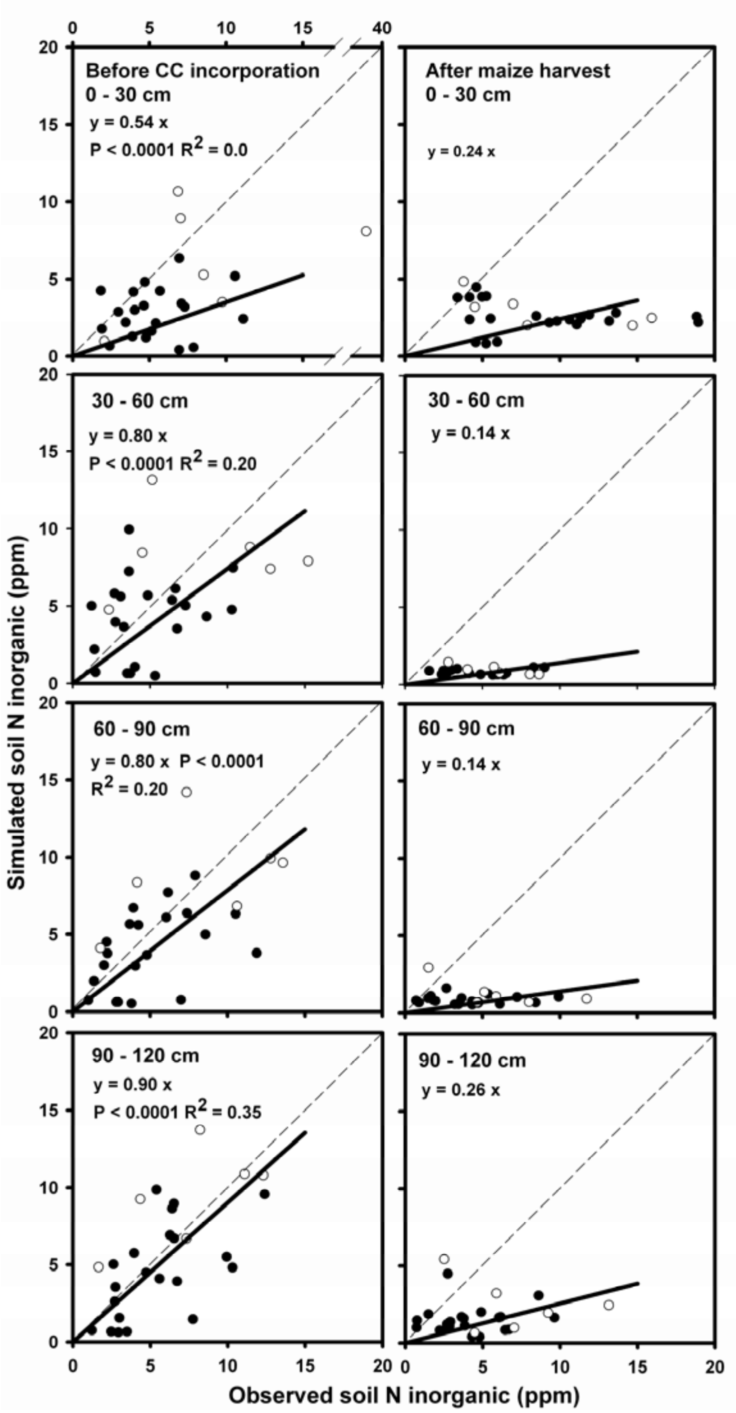

Figure 6. Measured and simulated soil inorganic N in the soil profile (0 to 1.2 m) before cover crop incorporation in spring and at maize harvest. Open symbols represent maize alter fallow. Closed symbols represent maize after a cover crop.

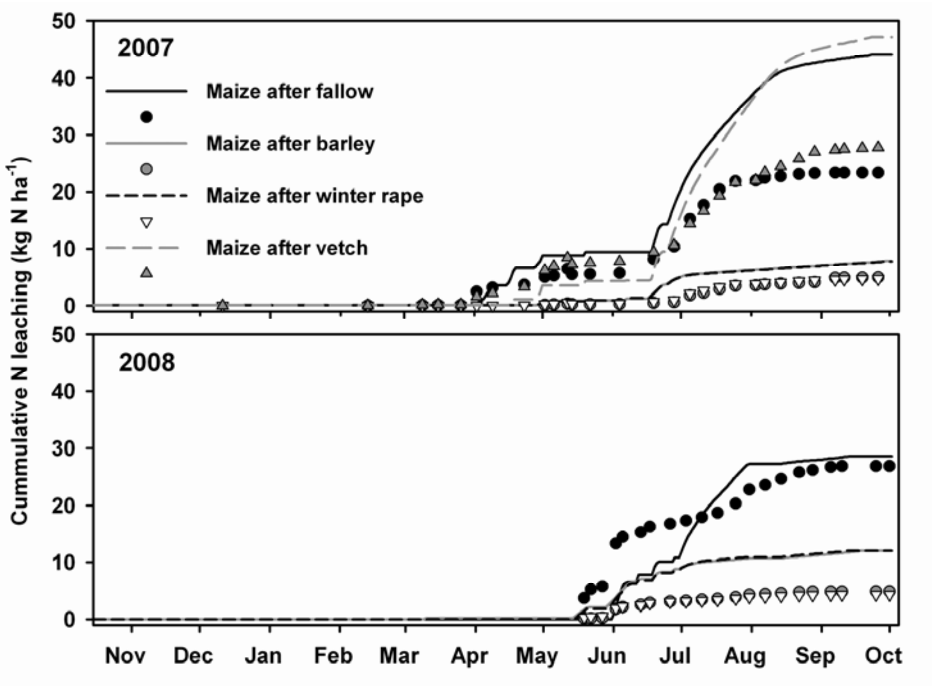

Figure 7. Cumulative N leaching in drainage water measured from the lysimeters (symbols) and simulated (lines).

Scenarios of cover crop use in La Violada watershed

The scenarios of cover crop use in La Violada watershed were simulated after the model had been calibrated and considered that provided a correct simulation of drainage, N leaching and maize grain yield. As maize grain yields were overestimated by the model and some overestimation of N leaching was found when maize was grown after a cover crop, the interpretation of results must be regarded with care.

Relevance of the rate of N fertilizer applied

N leaching in continuous maize increased with increasing rates of N applied (Figures 8 and 9). When no cover crop was grown, the average N leaching in drainage ranged from 58 kg N ha^{-1} with 250 kg ha^{-1} of N fertilizer applied to 111 kg N ha^{-1} leached at the highest N rate (350 Kg N ha^{-1}) (Figure 8). When using cover crops, N leaching was reduced approximately by half. (29 kg N ha^{-1} with 250 kg N ha^{-1} applied; 65 kg N ha^{-1} with 350 kg N ha^{-1} applied). The results indicate that lowering the N rate applied to maiz in monoculture is not sufficient to reach acceptable levels of N mass exported in drainage water, that were still high (58 kg N ha^{-1}). When fertilizer N was applied at the highest rate, the use of cover crops reduced N leaching to levels similar to the control at the lowest N rate. The combined effect of a reduced N rate and the use of cover crop was the most efficient strategy with only 29 kg N ha^{-1} lost. Using a cover crop reduced maize grain yield on average by 0.7 Mg ha^{-1} although differences occurred between years. The decrease in yield increased with the lower fertilizer N rates applied.

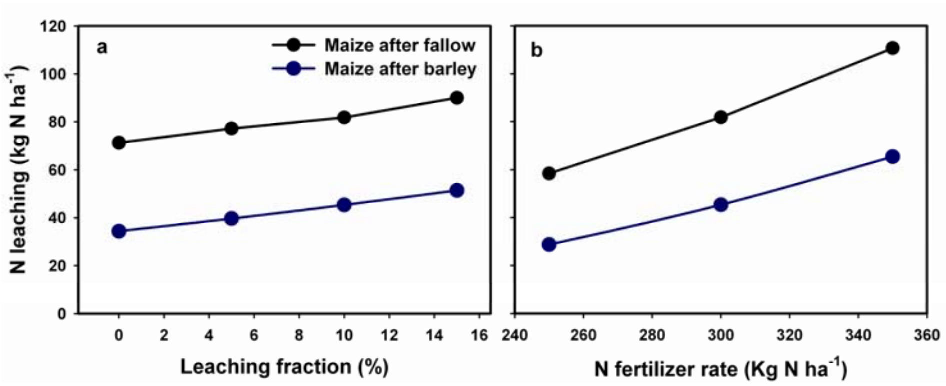

Figure 8. Average N leaching across the 13 maize growing seasons as a function of the leaching fraction of irrigation water applied (a) and as a function of the N fertilizer rate (b).

Relevance of the type of soil

N leaching during maize growing season was very sensible to the type of soil used in the simulations (Figure 10). N leaching was highest with soil C (on average 144 kg N ha^{-1}), that is a shallow soil with a low water retention capacity. The use of the cover crops reduced N leaching in all soils, but to a lesser extent in soil C, that still had high leaching losses when using a cover crop (114 kg N ha^{-1}). In soils A and B, the use of cover crops reduced N leaching by almost 50 %. Maize grain yield was reduced when using a cover crop compared to fallow. However, the negative effect of growing a cover crop was lower in soils B and C, with a lower water retention capacity. Thus, in soil C maize grain yield was on average only 0.2 Mg ha^{-1} lower compared to fallow.

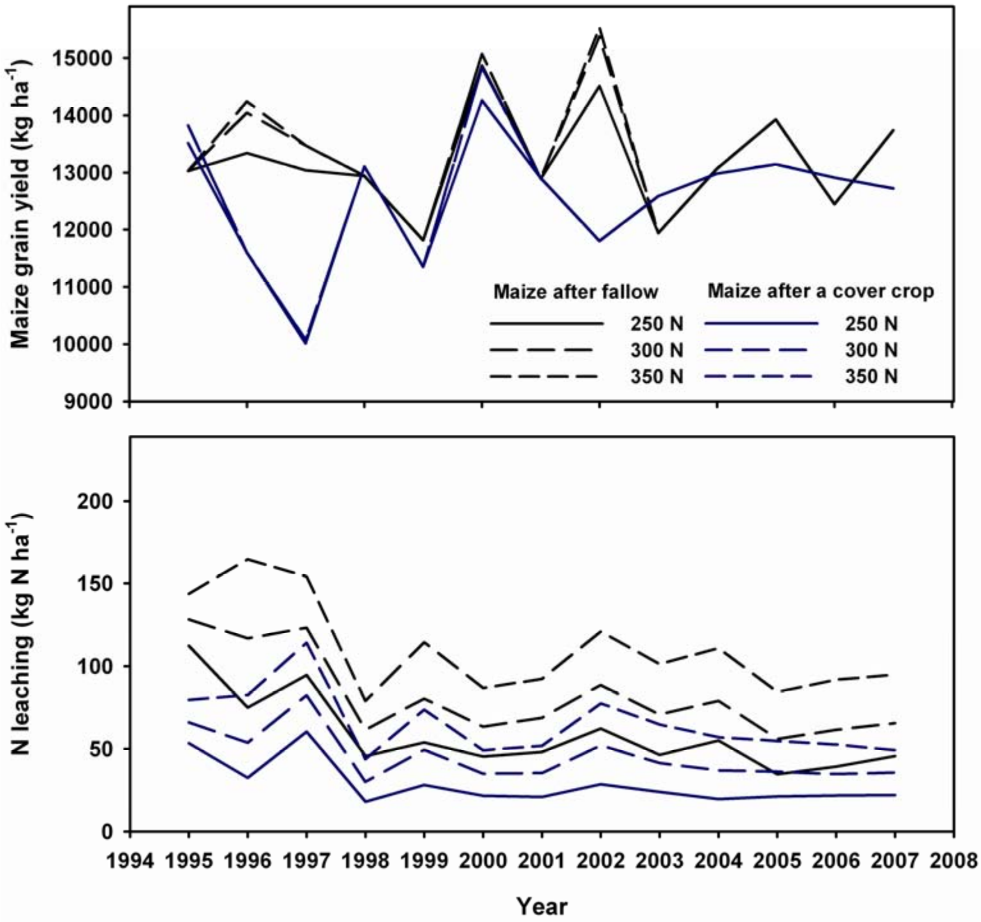

Figure 9. Maize grain yield and N leaching in drainage water for maize after fallow and after a barley cover crop at La Violada Irrigation District during a 14 year period depending on N rate applied.

Relevance of the leaching fraction of irrigation volumes applied

N leaching was dependent on the amount of water applied (Figures 8 and 11), increasing as the N leaching fraction increased. Growing a cover crop during the winter period was more relevant to decrease the N leaching than reducing the leaching fraction. At a given leaching fraction, growing a cover crops reduced N leaching by 50%. Yield was reduced in maize after a cover crop in some years, whereas it appears to be higher in others. On average, maize grain yields after barley were only 0.6 Mg ha^{-1} lower than after fallow.

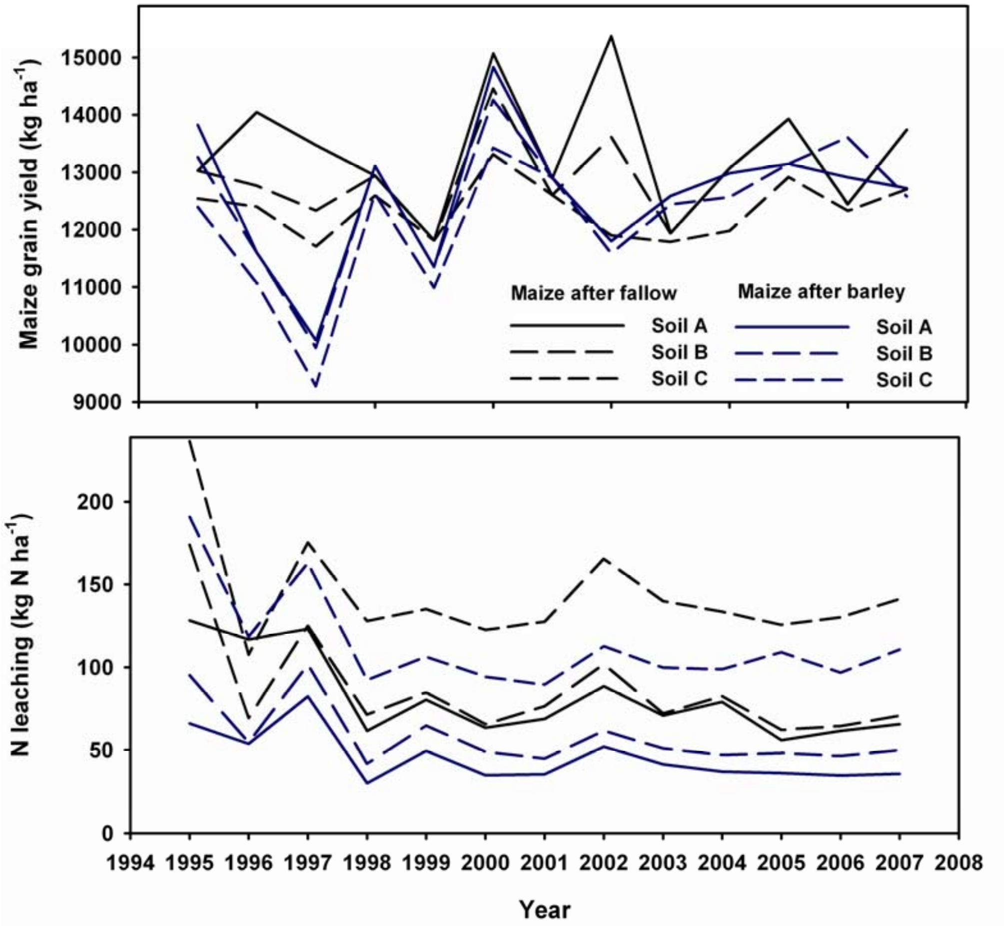

Figure 10. Maize grain yield and N leaching in drainage water for maize after fallow and after a barley cover crop for three different soil types at La Violada Irrigation District during a 14 year period.

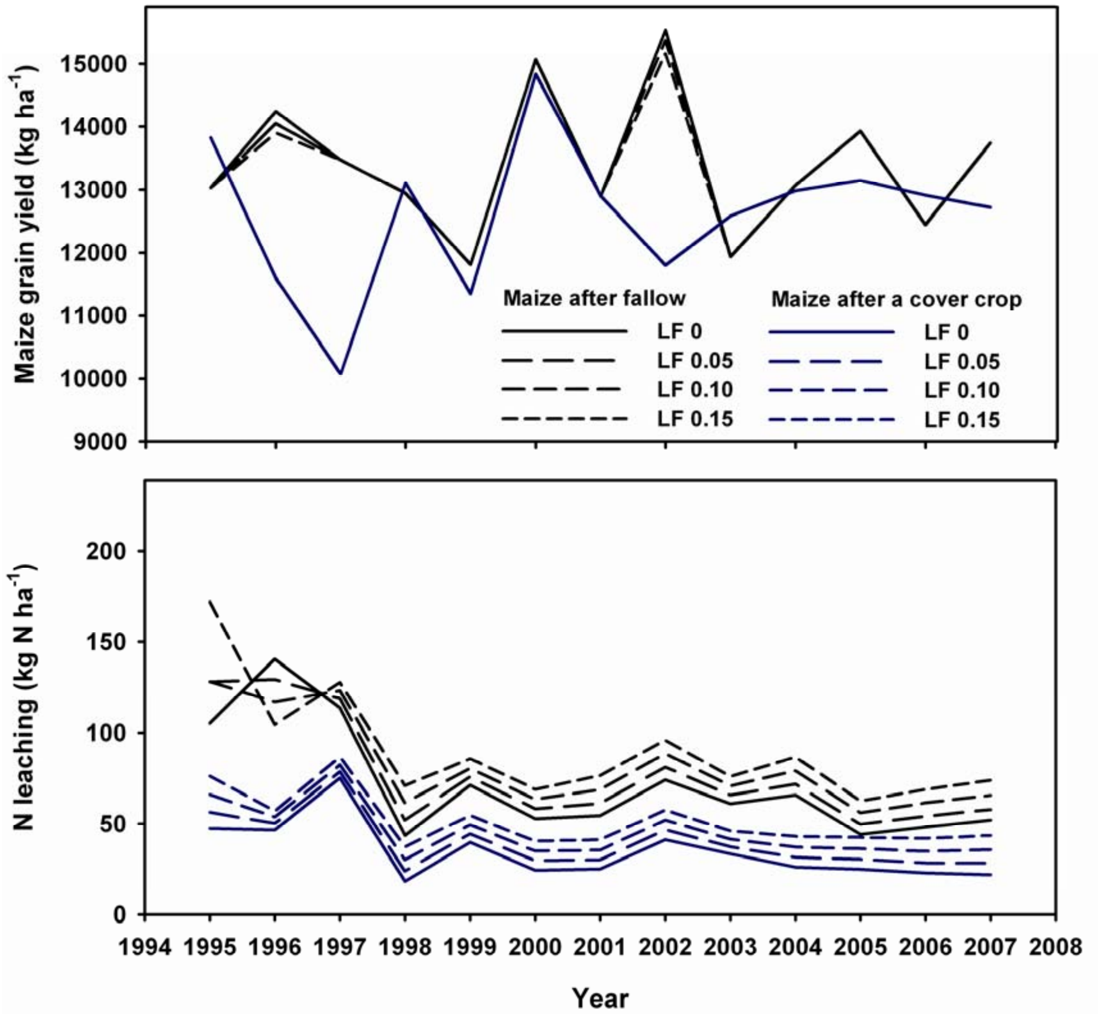

Figure 11. Maize grain yield and N leaching in drainage water for maize after fallow and after a barley cover crop at La Violada Irrigation District depending on the leaching fraction (LF) used to calculate the irrigation requirement during a 14 year period.

5. DISCUSSION

EPIC soil temperature subroutine

The adapted EPIC soil temperature subroutine improved soil temperature predictions compared to the current soil temperature subroutine in DSSAT, that on average overpredicted soil temperature by 7.5 ºC during the maize growing season, and by 1.6 ºC during the cover crop growth period. This greater overprediction of temperatures during the maize growing season compared to the winter period could be explained in part by the higher temperatures during spring and summer, and also by the irrigation events that can reduce soil temperature under field conditions due to a cooling effect of water applied by irrigation, whereas this effect was not taken into account in the DSSAT model. The use of the adapted EPIC soil temperature subroutine greatly improved the simulation of soil temperature by taking into account that irrigation and precipitation events decrease soil temperature. However, soil temperature was still overpredicted with EPIC by 2.7 ºC during the maize growing season.

The soil temperature simulation must be improved because this variable directly affects the mineralization of organic materials in the soil. The EPIC soil temperature subroutine does not take into account that evaporation of water from the soil decreases soil temperature. This can be relevant under conditions of high vapor pressure deficit, similar to those found in our experiments (Table 1) and in general for many arid or semiarid conditions with irrigation, and with frequent irrigation that results in a high soil water content and soil evaporation. Microclimatic changes during the sprinkler irrigation event are very important and usually last for 6 to 8 hour for irrigation events of 4 to 6 hours duration (Cavero et al., 2009). DSSAT overestimation of temperature can be of great impact on the estimation of soil and organic residue mineralization that greatly depend on temperature (Stroo et al, 1989). Maize total aboveground N mass is dependent on N availability and therefore affected by the simulation of soil temperature. Thus, maize N uptake was 10% higher than the observed data with the default DSSAT v.4.5 soil temperature subroutine (data not shown). However, with the adapted EPIC soil temperature subroutine N uptake was similar to the observed data.

Simulation of maize yield and N leaching when growing cover crops

Experimental data have shown that when growing maize after a non-legume winter cover crop, N availability to maize was reduced due to cover crop N uptake from the soil, the reduced N fertilization to maize after cover crops, and an incomplete or slow mineralization from the cover crop residues (Salmerón et al, 2010). The DSSAT v.4.5 model was not able to simulate this reduction in maize yield after a winter non-legume cover crop even when the adapted EPIC soil temperature subroutine was used. Although the total N uptake of maize plants was correctly simulated in the different cover crops treatments (except an 8 % overestimation in the barley treatment), the reduction in maize yield when growing barley and winter rape as winter cover crops was not correctly simulated. Yield reductions in maize were explained by the reduced number of grains and weight of grains. The model was able to simulate correctly the weight of grains in all cases except after barley, where was overestimated by 6 %. Number of grains was overestimated in maize after barley and winter rape by 12 and 6 %. Ovestimation of these two yield components explain the yield overestimation by 19 and 10 % observed by the model in barley and winter rape, respectively. The number of grains was the parameter that appeared to be less sensitive to the N deficiency.

It is possible that at the slight yield reductions observed in these experiments the model cannot show enough sensibility to detect these N deficiencies. The N stress effect on the set of number of grains in the model could be readjusted and compared to further data. Model studies under a range of N availability to maize have given good predictions under rainfed conditions in Iowa (Paz et al, 1999), Minnesota (Pang et al, 1998), and in Kenya (Keating et al, 1991) with CERES-Maize. Also good predictions were reported in semiarid conditions of Australia (Carberry et al 1989) and Turkey (Gerçek and Okant, 2010). Further studies at different N availability in irrigated maize in semiarid conditions are needed to test the model. It is interesting to note that maize yields were sensibly higher in our experiment (11 - 14 Mg ha^{-1}) than in most CERES-Maize studies (< 10 Mg ha^{-1}), and that studies with cover crops are scarce. Under growing conditions with high potential yields of maize, N availability and quantity over time could affect strongly maize yields due to the higher N demand. Although Bowen et al (1993) found that CERES-Maize accurately simulated mineralized N from green manure in Brazil, we did not observe enough sensitivity in the model after non-legume cover crops in irrigated semiarid conditions.

N uptake by maize plants was correctly simulated and can reflect the correct mineralization of soil and cover crops by DSSAT-CENTURY (Figure 12). The higher net N mineralization in the barley treatment compared to maize after fallow reflects the cover crop mineralization simulated by the model. This value was close to the estimated value of net N mineralized from the lysimeter experiment in both years (141 kg N ha^{-1} estimated in 2007, and 170 kg N ha^{-1}

simulated by the model) (Salmerón et al, 2010). These results indicate that DSSAT-Century simulations of mineralization were not far from the experimental results. The CENTURY model has proved to simulate correctly the soil C in long term simulations (Kelly et al, 1997; Smith et al, 1997), but little information exist about its use for N balance simulations in the short term. Gijsman et al (2002) observed that CENTURY predicted with accuracy soil inorganic N after short term simulations with fresh organic residues. Difficulties to adequately simulate the effect of mineralization from organic sources and its consequences in crops yields have been found in other studies (Corbeels et al, 1999; Cavero et al, 1997; Radke et al, 1991; Andren and Paustian, 1987). More detailed experiments with fresh organic residues or cover crops added and soil inorganic N measured over time should be needed in order to better study the DSSAT-CENTURY simulations under the irrigated conditions of this experiment. Residual soil N at maize harvest was underestimated by 75 kg N ha^{-1}. The simulated lower soil N content was probably related to the fact that in the model there is not limit in the crop N uptake from the soil. Thus, very low values (< 2 mg kg^{-1}) of soil inorganic N were simulated by the model in the barley treatment (Figure 12). Under field conditions, maize roots under full irrigated conditions do not deplete all the soil N because there is no need for such an extensive root growth in an environment plenty of available water. The fact that the maize plants were able to deplete N from the soil to such low values could partially explain the lack of yield reduction observed in maize after barley and winter rape.

The decrease in N leaching due to the growth of winter cover crops was correctly predicted by the model but the absolute values were overpredicted. The overestimation of N leaching could be explained by the fact that experimental data comes from a drainage lysimeter, where some preferential flow in drainage could occur. In any case, the correct simulation and response of the model to cover crop effect on N leaching indicates the feasibility of the model to study cover crop effects in N leaching.

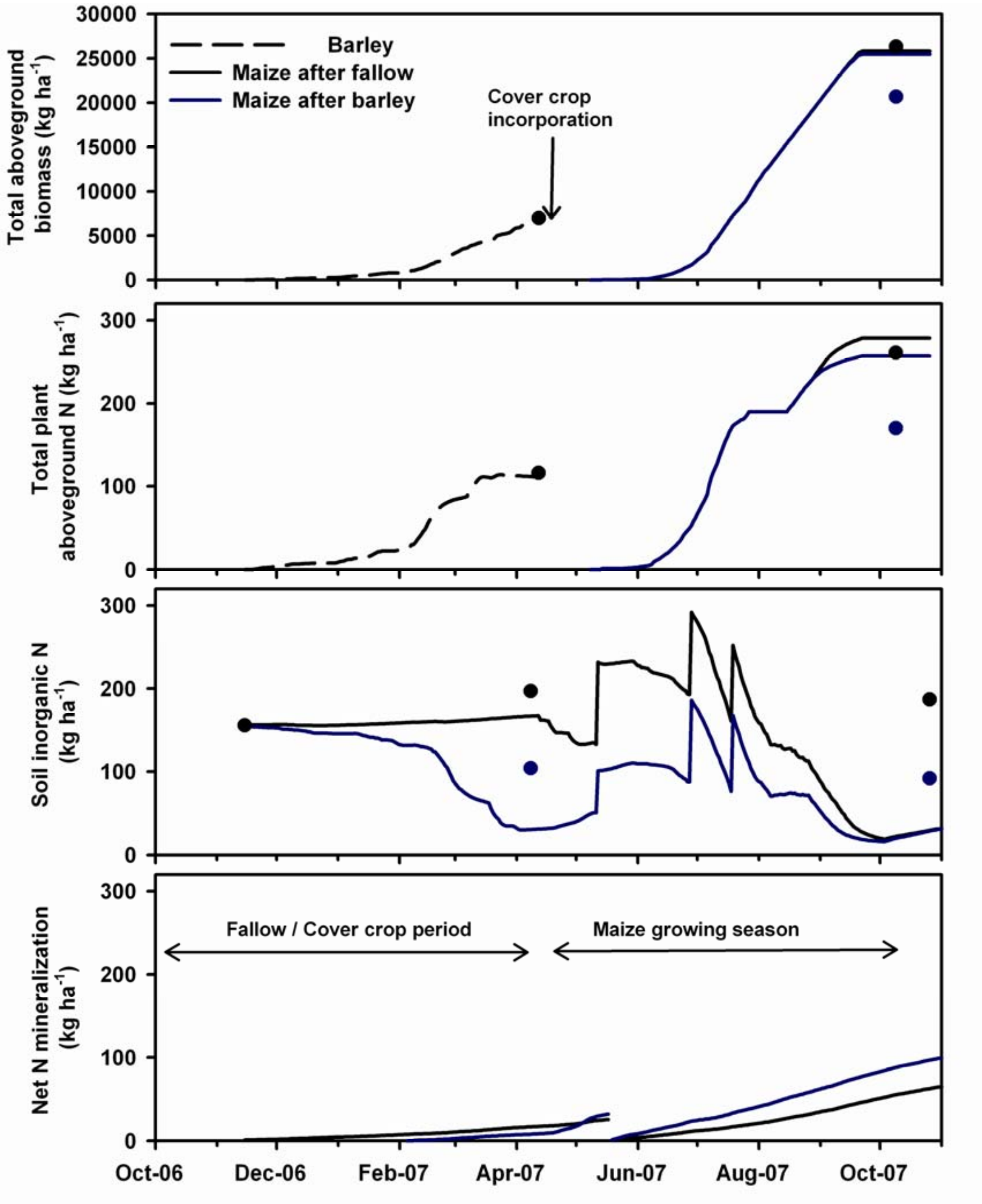

Figure 12. Evolution of cover crop and maize biomass production, N content in the aboveground biomass, soil N content, and net N mineralization. Data from the lysimeter experiment, maize growing season 2008. Symbols represent observed data.

Scenarios of cover crop use in La Violada watershed

The model allowed studying N leaching and maize grain yield in maize after fallow and after a cover crop in different scenarios in La Violada Irrigation District. N leaching was reduced in maize after a cover crop compared to maize after fallow at all rates of N fertilizer in all years. This indicate that cover crops could be useful in La Violada irrigation District, even maintaining the high N rates used in this area, that often reach values of 400 kg N ha^{-1} (Isidoro et al, 2006). The reduction in N leaching is explained by the depletion of soil inorganic N by cover crops and the reduction in soil water content due to cover crop evapotranspiration. In the 14 years of the study maize grain yields were reduced by 0.7 Mg ha^{-1} in average when a cover crop was grown. However, this yield reduction was relatively small compared to the beneficial effects of the cover crops in reduced N leaching risks in drainage water. Improved predictions of maize yields after a cover crop are needed in order to better study cover crop effects on maize yields.

The study of different soils indicated how cover crops can greatly reduce N leaching for all kinds of soil types used. However, for the soil with the lowest water retention capacity (Soil C), N leaching was still very high (above 100 kg N ha^{-1}). In order to avoid these high N leaching risks, other crops with lower N requirements than maize should be grown in soils with such high N leaching potential. The positive effect of the cover crops reducing N leaching was relatively higher in soils with a higher water retention capacity. On the other hand, the use of cover crops in soil C was able to maintain yields similar to the control and even higher some years.

The study of the leaching fraction interaction with the use of cover crops indicated that cover crops can reduce N leaching regardless of the amount of water applied. These results indicate that even with an optimum water management, high leaching risks exist for the soils present in la Violada Irrigation District, and that cover crops can be a useful tool in these high leaching risk situation. Maize grain yield was hardly affected at the range of leaching fractions studied, but yields were on average 0.6 Mg ha^{-1} lower in maize after a cover crop.

This study demonstrates the ability of the cover crops to reduce N leaching at the high rates of N fertilizer used in La Violada Irrigation District, but also under well managed conditions in terms of split N fertilization and irrigation. The reported yield reduction of maize yields after a cover crop appears to be minimum compared to the beneficial effects of the cover crop use in N leaching. Thus, great improvements in the N mass in the return flows from this watershed should be expected with the inclusion of cover crops in rotation with maize.

6. CONCLUSIONS

The modification of the soil temperature subroutine in DSSAT v.4.5 based on the adapted EPIC soil temperature subroutine improved the simulation of soil temperature in the irrigated semiarid conditions of the experiment.

Although the total N uptake of maize plants was correctly simulated in the different cover crops treatments, the simulated reduced N uptake of maize when growing barley and winter rape as winter cover crops was not reflected in a simulated reduction of maize yield. Consequently, the DSSAT v.4.5 model was not sensitive enough to simulate the reduction in maize yield after a winter non-legume cover crop at the range of maize yield reductions studied (10 – 20 % yield reduction).

The decrease in N leaching due to the growth of winter cover crops was predicted by the model although absolute values were overestimated, so the model can be used to predict N leaching in maize-cover crops rotations.

This study demonstrates the ability of the cover crops to reduce N leaching at the high rates of N fertilizer used in La Violada Irrigation District, but also under well managed conditions in terms of split N fertilization and optimum irrigation management. With the inclusion of cover crops in rotation with maize, great improvements in the N mass in the return flows from this watershed should be expected.

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Capítulo 6

Discusión general

Capítulo 6: Discusión general

En esta tesis se han evaluado distintas estrategias para reducir las pérdidas de N por lavado en cultivos de maíz y alfalfa, los cultivos extensivos económicamente más importantes en los regadíos del Valle del Ebro.

En primer lugar se ha estudiado la viabilidad de las aplicaciones de purín porcino durante el periodo de crecimiento de la alfalfa, en términos de productividad y calidad del forraje y en cuanto a la calidad de las aguas de drenaje. En segundo lugar se han cuantificado los efectos de los cultivos cubierta invernales en monocultivo de maíz en cuanto al rendimiento del maíz cultivado posteriormente y a las pérdidas de N por lavado. Por último, se ha calibrado y utilizado el modelo DSSAT para simular el efecto que los cultivos cubierta invernales tienen en el monocultivo de maíz.

En este apartado se discute de forma conjunta los resultados obtenidos.

1. Aplicación de purín porcino durante el periodo de crecimiento de la alfalfa. Efectos sobre el rendimiento de la alfalfa y sobre el medioambiente.

El purín porcino es habitualmente aplicado a cultivos de cereales no leguminosos como el maíz, donde los efectos de esta práctica han sido ampliamente estudiados (Daudén y Quílez, 2004; Eghball y Power, 1994). En este trabajo se aplicaron dosis de purín durante el periodo de crecimiento de la alfalfa, después del primer corte (finales Abril) y después del tercer corte (finales Junio), observándose un rendimiento acumulado después de dos años de aplicaciones similar al tratamiento control (sin purín porcino). Asimismo, la calidad del forraje, evaluado por la proteína bruta, no se vio afectada. Las dosis aplicadas de purín en este trabajo (22 a 96 m^3 ha^{-1}) fueron tan elevadas como las de otros ensayos en los que se han observado reducciones del rendimiento de alfalfa tras aplicaciones de purín porcino (Lamb y col., 2005) y purín vacuno (Daliparthy y col., 1994). Sin embargo, las condiciones de cultivo bajo riego de la alfalfa en el Valle del Ebro permiten el riego casi inmediato tras la aplicación del purín, lo que probablemente evita los efectos adversos asociados a toxicidad o salinidad observados por otros autores (Lamb y col., 2005; Diez y col., 2004; Daliparthy y col., 1994). En condiciones de suelos deficientes en P, las aplicaciones de purín de cerdo en alfalfa pueden incluso suponer un incremento del rendimiento (Lloveras y coll., 2004).

En cuanto a la calidad del agua de drenaje tras las aplicaciones de purín, cabe destacar que la mayor parte del drenaje se produjo durante el periodo de riego de la alfalfa, a diferencia de otros estudios en zonas no regadas dónde el 75% del drenaje ocurre durante el periodo intercultivo (Toth y col., 2006; Basso y Ritchie, 2005). Tras las aplicaciones de purín no se observó un incremento de la concentración de nitrato en el agua de drenaje, que fue muy baja durante el segundo y tercer año de cultivo de la alfalfa. Estas bajas concentraciones son similares a las encontradas en ensayos de alfalfa no fertilizada (Toth y Fox, 1998; Randall y col., 1997), pero son mucho menores a las observadas por otros autores con aplicaciones de N en forma orgánica o mineral (Toth y col., 2006; Basso y Ritchie, 2005; Daliparthy y col., 1994). Los resultados indican que las aplicaciones de purín en alfalfa en las condiciones de riego del Valle del Ebro tienen un bajo riesgo de lavado de nitrato, debido por una parte a la elevada capacidad de extracción de N de la alfafa (hasta 685 kg N ha^{-1} y año) por su elevada productividad, y a que la mayor parte del drenaje sucede durante la fase de crecimiento activo del cultivo. Asimismo, se observó un cambio significativo en el perfil isotópico del nitrógeno en la biomasa de la alfalfa de las parcelas que recibieron purín comparadas con el tratamiento control, debido a que una parte significativa del mismo procedía del purín aplicado y no de fijación simbiótica.

Las concentraciones de P en el agua de drenaje estuvieron en general por debajo de límite de eutrofización (0.001 mg P L^{-1}), lo que indica que la aplicación de purín porcino sobre alfalfa en crecimiento tiene un bajo riesgo de eutrofización de las aguas superficiales. Así, la masa total de P perdida en el agua de drenaje (0,035 kg P ha^{-1} $año^{-1}$) fue mucho menor que en un estudio en el que se aplicó estiércol de vacuno a la alfalfa (0.5 kg P ha^{-1} $año^{-1}$) (Toth y col., 2006). Sin embargo, el incremento observado de un 21% en el contenido en P total de la capa superficial del suelo (0 – 30 cm) tras dos años de aplicación de purín porcino indica que las aplicaciones de purín deberían estar basadas en las necesidades de P de los cultivos en la rotación, con el fin de no provocar una acumulación de P en el suelo que aumente el riesgo de pérdida de P (Toth y col., 2006; Eghball y Power, 1999).

Los metales pesados no aumentaron significativamente en la biomasa cosechada de alfalfa, ni en el suelo tras las aplicaciones de purín durante dos años, lo que está de acuerdo con lo encontrado por otros autores en condiciones de cultivo similares (Berenguer y col., 2008)

2. Utilización de cultivos cubierta en monocultivo de maíz

Los cultivos cubierta en el periodo intercultivo de maíz no son una práctica habitual en el Valle del Ebro. Los resultados muestran que los cultivos cubierta estudiados produjeron biomasa y acumularon N en el rango alto de los datos obtenidos por otros autores (Kramberger y col., 2009; Maltas y col., 2009; Thomsen, 2005; Stenberg y col., 1999), lo que indica su viabilidad en las condiciones climáticas estudiadas con riegos suplementarios de 40 a 60 mm, fundamentalmente para asegurar la implantación de los cultivos.

Se ha observado que una implantación adecuada del cultivo cubierta es esencial para un buen desarrollo del mismo. Las fechas de siembra tardías (noviembre) pueden tener un efecto negativo en cultivos como la nabina y colza, que ya están fuera de su época de siembra. La siembra directa de los cultivos cubierta tras la cosecha de maíz permitió adelantar la fecha de siembra en 8 – 12 días en comparación con una siembra tras las labores de preparación del suelo convencionales, debido a que en ocasiones es preciso esperar a que el suelo tenga menor humedad para poder realizar las labores. El adelanto de las fechas de siembra incrementó la biomasa producida de todos los cultivos cubierta el primer año. Sin embargo, en el segundo año hubo un efecto negativo de la siembra directa en los cultivos cubierta de veza, nabina y colza ya que la gran cantidad de residuos de maíz dio lugar a una mala implantación de estos cultivos.

La cebada tuvo una buena implantación tanto con siembra directa como con siembra tras laboreo convecional y fue la especie que tuvo las más altas producciones de biomasa y acumulación de N, debido a su mayor vigor inicial y rusticidad. Sin embargo, este cultivo es el que mostró la relación C/N más elevada (de 17 a 29), que se ha relacionado con procesos de inmovilización (Kuo y Jellum, 2000; Kaye y Hart, 1997; Ranells y Wagger, 1996). Los cultivos de colza y nabina son capaces de producir cantidades adecuadas de biomasa (≈ 2 t ha^{-1}) con contenidos adecuados de N (≈ 70 kg ha^{-1}) y con una menor relación C/N (13 a 18), pero para ello es necesario que tengan una buena implantación. La veza mostró las relaciones de C/N más bajas (10 a 13) y acumulación de N en la biomasa similar a la colza y la nabina.

La utilización de especies no leguminosas como cultivo cubierta tuvo un efecto negativo en el rendimiento del maíz, en especial en el caso de la cebada. La cebada redujo la producción de maíz en 2,8 t ha^{-1} cuando la fertilización nitrogenada aplicada al cultivo siguiente de maíz se redujo en 157 kg N ha^{-1} en promedio en uno de los ensayos. Cuando la fertilización aplicada al maíz cultivado tras cebada se redujo en 50 kg N ha^{-1}, la producción de maíz se redujo en promedio en 2,4 t ha^{-1}. La nabina redujo el rendimiento del maíz de forma similar a como lo hizo la cebada cuando la fertilización nitrogenada aplicada al cultivo siguiente de maíz se redujo en 140 kg N ha^{-1}. Sin embargo, cuando la fertilización aplicada al maíz cultivado tras nabina se redujo en 50 kg N ha^{-1}, la producción de maíz solo se redujo en promedio en 0,8 t ha^{-1} y no difirió del control. La colza redujo el rendimiento del maíz en 1 t ha^{-1} en uno de los dos ensayos realizados en los que la fertilización aplicada al maíz cultivado tras colza se redujo en 50 kg N ha^{-1}. Las reducciones en el rendimiento del maíz fueron debidas a una menor disponibilidad de N, lo que fue posible detectar por medio de las medidas de SPAD en hoja, el nitrato en la base del tallo al final del cultivo, y la medida del contenido de N en la biomasa de la planta de maíz.

La veza no redujo el rendimiento del maíz aunque la fertilización aplicada al maíz cultivado tras veza se redujo en 43 o 50 kg N ha^{-1}.

Cuando la mineralización del N de fuentes orgánicas no está bien sincronizada con la demanda de N de los cultivos se pueden producir deficiencias de N en los cultivos (Magdoff, 1991). La sincronización es especialmente relevante cuando la cantidad de N a aportar por la fuente orgánica de N es alta y cuando se trata de cultivos de crecimiento determinado y con una gran absorción de N en un periodo corto de tiempo como el maíz. Se ha observado una menor disponibilidad de N para los cultivos tras la incorporación al suelo de cultivos cubierta con alto ratio C:N (Starovoytov y col., 2010; Sainju y col., 2005; Baggs y coll, 2000). Valores de este ratio superiores a 25 producen inmovilización de N (Kaye y Hart, 1997; Ranells y Wagger, 1996). Una incorporación anterior de la cebada o su combinación en mezcla con veza podrían mejorar la mineralización del N (Sainju y col., 2005; Ranells y Wagger, 1997).

Los resultados indican que el efecto de los cultivos cubierta en el rendimiento del cultivo siguiente de maíz no dependen únicamente de la dosis fertilizante aplicada y del N en el suelo en el momento de la siembra. La calidad del cultivo cubierta incorporado parece tener una gran importancia, así como las condiciones meteorológicas y de suelo, ya que ambas afectan directamente a los procesos de mineralización del nitrógeno contenido en los residuos del cultivo cubierta, lo que dificulta la estimación de la dosis de N fertilizante óptima tras un cultivo cubierta. Por este motivo, la utilización de herramientas de diagnóstico de la fertilización nitrogenada puede resultar imprescindible para permitir ajustar la dosis de N fertilizante a aplicar en maíz tras cultivos cubierta. Las medidas de SPAD fueron capaces de detectar deficiencias de N que dieron lugar a disminuciones del rendimiento de maíz en los dos ensayos. Esta herramienta ha mostrado ser útil para indicar deficiencias en maíz tras cultivos cubierta (Miguez y Bollero, 2006).

La baja precipitación observada durante los periodos intercultivo estudiados (< 130 mm) hizo que el lavado de N se produjera fundamentalmente durante el cultivo de maíz. Esto está de acuerdo con experimentos realizados en la zona (Yagüe y Quílez, 2010). Estudios a nivel de cuenca indican que si bien la mayor parte del N se pierde durante el periodo de riego (que coincide con el cultivo de maíz) también se pierde N durante el periodo de no riego (que coincide con el periodo intercultivo del maíz) (Causapé y col., 2006; Cavero y col., 2003). El patrón de pérdida de N es muy diferente del de zonas húmedas en las que la mayor parte del N se pierde durante el periodo intercultivo del maíz debido a las altas precipitaciones invernales.

El lavado de N depende del volumen de agua de drenaje y de la concentración de N en el agua de drenaje. En general la reducción del lavado de N en maíz se ha relacionado más con la reducción del volumen de drenaje que con la reducción de la concentración de N (Díez y col., 2000; Bjorneberg y col., 1996). La reducción del riego aplicado para reducir el lavado de N ha dado lugar en ocasiones a reducciones del rendimiento del maíz (Díez y col., 2000). Klocke y col. (1999) observaron altas pérdidas de N por lavado bajo condiciones óptimas de manejo y concluyeron que es difícil reducirlas.

Todos los cultivos cubierta redujeron el contenido en agua y N del suelo en primavera, reduciendo así el riesgo de pérdidas de N por lavado. Los resultados obtenidos en el ensayo de lisímetros indican que las especies no leguminosas estudiadas, cebada y nabina, demostraron una gran capacidad para reducir el lavado de nitrato en relación al tratamiento control. Sin embargo, la veza no redujo el lavado de nitrato. La reducción del lavado de N fue debida principalmente a una reducción de la concentración de nitrato en el agua de drenaje ya que el volumen de drenaje fue afectado mínimamente por el cultivo cubierta. La reducción de la concentración de N en el agua de drenaje se observó durante todo el periodo de cultivo del maíz. Sin embargo, las reducciones de N lavado observados en otros trabajos con cereales como cultivos cubierta en maíz se han observado principalmente durante el invierno debido al mayor drenaje durante dicho periodo (Ball-Coelho y col., 2004; Brandi-Dohrn y col, 1997; McCracken y col., 1994; Martínez y Guiraud, 1990). Dado que es necesario aplicar un exceso de agua de riego para lavar las sales, el uso de cultivos cubierta que reducen la concentración de N en el agua de drenaje es la mejor manera de reducir el lavado de N manteniendo un adecuado balance de sales en los suelos regados.

El estudio del N en el suelo en horizontes profundos puede ser utilizado para estudiar el movimiento de N en el suelo y el riesgo de lavado (Thorup-Kristensen y col., 2009). En el ensayo realizado en la parcela, los muestreos profundos realizados en 2008 no fueron capaces de detectar apenas diferencias entre tratamientos en el momento de la cosecha de maíz. Por lo tanto, la reducción del N en el suelo tras los cultivos cubierta en primavera es el factor más limitante para reducir las pérdidas de N durante el cultivo de maíz. La utilización de un cultivo cubierta que reduzca el N inorgánico residual del suelo tras la cosecha del maíz junto con un manejo adecuado de la fertilización nitrogenada en el siguiente cultivo de maíz pueden ser una forma eficaz de reducir el lavado de N sin comprometer las necesidades de agua y N del maíz.

3. Utilización de modelos de simulación.

Generalmente los modelos de simulación de cultivos requieren de una calibración que permita su uso. En este trabajo se observaron algunas limitaciones del modelo. Algunas de ellas se solventaron con pequeñas modificaciones.

Dado que la mineralización de la materia orgánica depende de la temperatura y contenido de agua del suelo, ambos procesos deben ser correctamente simulados. La evaporación del agua del suelo disminuye la temperatura del suelo. Esto puede ser relevante en condiciones de alto déficit de presión de vapor y con riegos frecuentes que dan lugar a un contenido alto de agua en el suelo y a una elevada evaporación del agua del suelo. El modelo DSST no tiene en cuenta estos procesos, por lo que la temperatura del suelo simulada fue en promedio 7,5 ºC mayor a la observada durante el periodo de crecimiento de maíz. La incorporación de la subrutina de simulación de la temperatura del suelo del modelo EPIC mejoró la predicción de la temperatura, que fue sólo 2,7 ºC superior a la observada. La mejora de la simulación fue debida probablemente a que el modelo EPIC tiene en cuenta que los periodos de precipitación o riego disminuyen la temperatura del suelo. Sin embargo, no tiene en cuenta el efecto de enfriamiento cuando se evapora agua del suelo, especialmente relevante en condiciones de alto déficit de presión de vapor y riego. Podría ser interesante una mejora de DSSAT que considere el efecto de este proceso sobre la temperatura del suelo.

Si bien la calibración del modelo permitió una adecuada simulación del rendimiento y crecimiento del maíz en el tratamiento control (suelo desnudo durante el invierno) y de la producción de biomasa y acumulación de N de los cultivos cubierta, el rendimiento de maíz tras los cultivos cubierta no leguminosos se sobrestimó. Los resultados observados en los ensayos experimentales indicaron una reducción del rendimiento del maíz del 10 – 20 % tras los cultivos de cebada y nabina debido a una deficiencia de N. Sin embargo, el modelo no fue suficientemente sensible para simular esta reducción en el rendimiento. El parámetro que principalmente determinó esta reducción del rendimiento fue el número de granos, que el modelo sobrestimó cuando se cultivaron dichos cultivos cubierta. Otros estudios realizados con CERES-Maize en un rango de disponibilidad de N han dado buenos resultados en condiciones sin riego (Paz y col., 1999; Pang y col., 1998; Keating y col., 1991). También se han observado buenos resultados en condiciones semiáridas de Australia (Carberry y col., 1989) y Turquía (Gerçek y Okant, 2010). Sin embargo, los rendimientos del maíz en nuestra zona de trabajo (11 a 14 t ha^{-1}) son sensiblemente superiores a los de estos ensayos (<10 t ha^{-1}). En condiciones de cultivo de altos rendimientos potenciales del maíz, la disponibilidad de N en cantidad suficiente y en el momento adecuado pueden afectar de forma importante al rendimiento del maíz debido a la fuerte demanda de N por parte del cultivo.

La correcta simulación del contenido de N en maíz tras cultivos cubierta puede indicar la correcta simulación de la mineralización del suelo y los cultivos cubierta del modelo DSSAT-CENTURY. El modelo simuló una mineralización de N mayor tras cultivos cubierta en comparación a un suelo desnudo debido a la mineralización del N de la biomasa del cultivo cubierta. El modelo CENTURY se ha utilizado con éxito para simular el balance de C del suelo en largos periodos de tiempo (Kelly y col., 1997; Smith y col., 1997), pero existe menos información sobre simulaciones del balance de N en simulaciones a corto plazo. Gijsman y col. (2002) observaron que CENTURY predecía con exactitud el N mineral en el suelo después de la aplicación de residuos orgánico de cultivos, Sin embargo, numerosos estudios han encontrado dificultades en la simulación de los procesos de mineralización de N de fuentes orgánicas y su efecto sobre los cultivos (Corbeels y col., 1999; Cavero y col., 1997; Radke y col., 1991; Andren y Paustian, 1987). Son necesarios ensayos más detallados de la evolución del N en el suelo para evaluar el modelo DSSAT-CENTURY en rotaciones de cultivos cubierta-maíz en las condiciones bajo riego en clima semiárido.

El modelo simuló adecuadamente la disminución del lavado de N debida al uso de cultivos cubierta, si bien en términos absolutos los valores se sobrestimaron. El modelo se usó para estudiar el efecto del uso de los cultivos cubierta sobre el lavado de N y el rendimiento del maíz en la cuenca de la Violada, que es una zona regada del Valle del Ebro que ha sido monitorizada y estudiada durante las últimas décadas (Isidoro et al., 2006; Bellot et al., 1989). Las simulaciones mostraron que con el uso de cultivos cubierta se pueden lograr reducciones en el lavado del 50% con las dosis de N aplicadas estudiadas (250 a 350 kg N ha^{-1}). La reducción del N por lavado con el uso de los cultivos cubierta se debe a la extracción de N inorgánico del suelo y la reducción del agua del suelo por los cultivos cubierta. Las simulaciones mostraron que los cultivos cubierta disminuyen el lavado de forma diferente en los distintos suelos de la cuenca de la Violada. Asimismo, las simulaciones mostraron que los cultivos cubierta reducen el lavado de N en todas las fracciones de lavado estudiadas. Los rendimientos de maíz se redujeron tras los cultivos cubierta en promedio en 0,6 – 0,7 t ha^{-1} cuando se usaron cultivos cubierta. Sin embargo, esta reducción puede considerarse menor en comparación con los efectos positivos en la reducción del lavado. Las simulaciones mostraron que los cultivos cubierta pueden ser una herramienta eficiente para reducir el lavado aún con dosis ajustadas y fraccionadas de N fertilizante (250 kg N ha^{-1}) y con un manejo óptimo del riego.

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Capítulo 7

Conclusiones generales

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1. Aplicación de purín porcino durante el periodo de crecimiento de la alfalfa. Efectos sobre el rendimiento de la alfalfa y sobre el medioambiente.

Las aplicaciones de purín porcino durante el periodo de crecimiento de la alfalfa no afectaron a la producción ni a la calidad del forraje de alfalfa después de dos años. La ausencia de efectos negativos, asociados normalmente a toxicidad del purín, se debe probablemente al efecto del lavado del purín mediante el riego posterior y a que el purín se aplicó inmediatamente después del corte cuando no había brotes en crecimiento.

Las altas extracciones de N de la alfalfa y su capacidad de adaptar la fijación de N atmosférico a la disponibilidad de N dieron lugar a concentraciones bajas de nitrato en el agua de drenaje incluso tras la aplicación de dosis altas de purín porcino (340 kg N ha^{-1}). Asimismo la masa y concentraciones de P exportadas en el agua de drenaje fueron muy bajas y no se vieron afectadas por las aplicaciones de purín. Tras dos años se observó un incremento del 21 % del P Olsen en la capa superficial del suelo (0 – 30 cm) como resultado de las aplicaciones de purín y de P fertilizante. Sin embargo, las aplicaciones de purín no incrementaron significativamente el contenido de Zn y de Cu en la capa superficial de suelo.

Los resultados indican que las aplicaciones de purín porcino durante el periodo de crecimiento de la alfalfa pueden incrementar la disponibilidad de superficie y el tiempo para la aplicación de este residuo ganadero en el Valle del Ebro sin efectos nocivos sobre el forraje de alfalfa ni tampoco sobre el medioambiente. Así, la aplicación de purín porcino en alfalfa puede incrementar la superficie destinada a la gestión de este residuo en torno a unas 100.000 ha en España y 70.000 ha en Aragón. Para evitar la acumulación de P en el suelo las aplicaciones de purín deberían estar basadas en las extracciones de P del cultivo (30 a 50 m^3 ha^{-1} $año^{-1}$, dependiendo de la riqueza del purín) o bien considerar las extracciones de P en los diversos cultivos en rotación en la parcela dada la baja movilidad de dicho elemento.

2. Utilización de cultivos cubierta en monocultivo de maíz.

Los cultivos cubierta fueron capaces de producir biomasa y acumular N en el rango alto (35 – 100 kg N ha^{-1} $año^{-1}$) de los valores observados en otras condiciones, demostrando la posibilidad de su cultivo bajo las condiciones semiáridas del Valle del Ebro. La siembra directa puede permitir producciones mayores de biomasa de todos los cultivos cubierta (cebada, nabina, colza y veza) y mayores extracciones de nitrógeno debido al adelanto en la fecha de siembra. Sin embargo, en el caso de la veza, la nabina y la colza la siembra directa puede reducir la producción de biomasa debido a una mala implantación del cultivo.

El uso de especies no leguminosas como cultivos cubierta redujo las perdidas de nitrato en el agua de drenaje. De igual modo, la reducción en el contenido de nitrato en el suelo tras los cultivos cubierta indica un menor riesgo de lavado cuando se introducen en la rotación. Sin embargo, es necesario profundizar en el uso de leguminosas como cultivo cubierta ya que la disminución del N en el suelo tras la veza indica que también puede reducir el riego de lavado, aunque en menor medida que las especies no leguminosas.

La utilización de cebada como cultivo cubierta presenta mayor riesgo de reducir el rendimiento de grano (descenso de 1 a 4 t ha^{-1}) en el maíz cultivado posteriormente debido a sus mayores extracciones de N y a la dificultad de que la mineralización del N contenido en la biomasa de la cebadas se sincronice con las necesidades de N del maíz. La utilización de nabina y colza junto con una disminución de 50 kg N ha^{-1} de N fertilizante respecto al control permitió obtener rendimientos en grano de maíz similares al tratamiento control. En cambio el uso de una especie leguminosa como la veza no afectó en ningún caso al rendimiento de grano del maíz cultivado posteriormente.

Es necesario mejorar el ajuste de las dosis de N fertilizante aplicado en maíz tras cultivos cubierta con el fin de evitar reducciones en el rendimiento de maíz. Los resultados indican que la utilización del SPAD puede ser una herramienta útil para detectar deficiencia en maíz en estas condiciones.

3. Aplicabilidad del modelo de simulación DSSAT para simular el ciclo del N en rotaciones de cultivos cubierta-maíz bajo condiciones de regadío en clima semiárido.

Los resultados observados indican que es recomendable la utilización de la subrutina de cálculo de la temperatura de suelo del modelo EPIC en el modelo DSSAT v.4.5, ya que mejoró de forma significativa la simulación de la temperatura del suelo en condiciones de regadío y en climas semiáridos similares a los del Valle del Ebro.

El modelo DSSAT v.4.5 puede ser utilizado para estudiar el impacto del uso de cultuvos cubierta en las pérdidas de N por lavado en el monocultivo de maíz. Sin embargo, es necesario mejorar el modelo para que simule correctamente el efecto negativo que se observó en el rendimiento del maíz tras algunos cultivos captura como cebada y nabina.

La aplicación del modelo a las condiciones edafoclimáticas de la cuenca regada de La Violada en el Valle del Ebro indican que los cutlivos cubierta pueden reducir el lavado de N de forma sustancial (50%) con distintas dosis de N aplicado (250 a 350 kg N^{-1} ha^{-1}) y con distintas fracciones de lavado.